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DETAILED CONTENTS.

PAGE

METHODS OF TRANSPORT OF RAW MATERIAL IN THE IRON INDUSTRY, WITH SPECIAL REFERENCE TO THE COST OF PRODUCTION OF PIG IRON. By J. F. APPELSTEDT (Dresden) . 1

The supply of raw material 2
The conditions governing the situation of an iron industry . . . 7
Import and export of raw material 9
Nature of raw materials to be considered in the provision of transport facilities 12
Economic working of transport arrangements 15
Long-distance transit 16
Ship transport 17
Railway transit 21
Storage of raw materials 23
Unloading the railway wagons 27
    Automatic unloaders 27
Costs of employing automatic unloaders as against those incurred when using ordinary wagons 30
Wagon-tips 33
Unloading from ships 34
Calculation of cost of plant and working expenses 38
    Consumption of current during one round of operations with the crane 38
    Cost of current 39
    Workmen's wages 39
The aerial ropeway 43
Calculation of cost of plant and working expenses of an aerial ropeway 45
        1. Wages 45
        2. Cost of current 45
        3. Cost of lubrication 46
        4. Cost of maintenance and repairs 46
        5. Standing charges 46
Blast-furnace charging 47
    Charging by means of hopper buckets 49
Plant "A" 54
Calculation of costs of installation and working 54
    I. Standing charges (depreciation and interest 5 per cent.) . . 54
        1. Ore bunkers 54
        2. Elevated railway over stock ground, piers, elevated railway with lines, slag cement 54
        3. Suspended railway plant 55

PAGE
4. Travelling platforms 55
5. Operation of transporting bogies 55
6. Drive for coke-skips 55
7. Working of inclined hoists 56

II. Wages 56
1. For discharging ore wagons into bins and on storage ground 56
2. For withdrawing ore from bunkers 56
3. Inclined hoist drivers 56

III. Repairs, maintenance, and renewals 57
1. Ore bunkers, elevated railway 57

IV. Lubricants and cleaning material 57

V. Current consumption 57
1. Lighting of ore bunkers and of store 57
2. Bogies 57
3. Power consumption for travelling platforms 57
4. Power consumption for coke-bucket cranes 57
5. Lighting under ore bunkers 57
6. Four inclined hoists 58

Summary of initial costs, also of transport charges per annum . 58

Transport charges per 1 ton of pig iron 58

Plant "B" 58
Summary of initial costs, also of transport charges per annum for plant "B" 58
Transport charges per ton 59

Plant "C" 59
Summary of transport charges per annum 60
Transport charges per ton of pig iron 60

Charging by electric telpher line 60

Plant "D" 62
Ore transport 62
Coke transport 63

Summary of annual transport charges 63

Transport charges per ton of pig iron 64

Comparison of plants described 64

ELECTRIC FURNACES FOR HEATING STEEL. By ALCAN HIRSCH (New York) 68

Scope of the Report 68

Electric furnaces working below 980° C. 70

Furnaces with permanently connected resistors 73

Method of calculating load 76

Electric furnaces working above 980° C. 83

Furnace walls and linings 84

Selection of type of furnace 91

Considerations of cost 93

PAGE

ROTARY BEND TESTS, ALTERNATING BEND TESTS, AND REPEATED SHOCK TESTS. By E. NUSBAUMER (Paris) 94

Introduction 94

I. Historical 96
- 1. General considerations 96
- 2. Influence of the chemical composition 100
- 3. Influence of treatment 102
- 4. Influence of shape of test-pieces 103
- 5. Influence of the rate of repetition of the stresses 103
- 6. Mode of fracture 104
- 7. Relation between alternating stress tests and simple impact tests 104

II. Description of apparatus and of the materials investigated . . . 105
- 1. Repeated impact tests 105
- 2. Endurance tests 107
- 3. Vibration tests 109
- 4. Simple impact tests 113
- 5. Chemical composition of the steel test-pieces 113
- 6. Treatment 114

III. Details of the experiments 115
- 1. Repeated impacts 115
  - (a) Influence of the depth of fall and of the rate of the repetition of the stress 118
  - (b) Influence of chemical composition 118
  - (c) Influence of treatment 119
  - (d) Influence of the brittleness of the metal on the resistance to repeated shocks 121
  - (e) Mechanism of rupture and influence of the texture on the resistance to repeated shock 125
- 2. Endurance (rotary bending) 139
  - (a) Results of the tests 141
  - (b) Influence of the brittleness of the metal on its resistance to rotary bending stresses 141
  - (c) Must a steel have been worked beyond its elastic limit to break under the rotary bend test? 143
  - (d) Mode of fracture 144
- 3. Vibrations 144
  - (a) Results of the tests 154
  - (b) Influence of the brittleness of the metal on its resistance to vibrations 157
  - (c) Mode of fracture 157
  - (d) The relation between bend tests and tensile tests . . 158
  - (e) Moduli of elasticity 164

Conclusions 164

PAGE

INFLUENCE OF RIVETING ON THE STRESSES IN THE RIVET AND ON THE STRENGTH PROPERTIES OF THE RIVET MATERIAL. By HANS RUDELOFF (Gross-Lichterfelde, Berlin) . 170

I. Scope of experiments 172
The test material and its preparation 173
Method of carrying out the tests 176
1. Determination of the rivet stresses 176

II. Determination of the strength properties of the raw material and of the driven rivets 183

III. Results of tests 190
1. The rivet stress 190
(a) Elongation of the head 190
(b) Shrinkage of the rivet 191
2. Strength properties of the material used and of the driven rivets 200
(a) Raw material 200
(b) Finished rivets 204

IV. Summary 214

THE GASES OCCLUDED IN LIQUID STEEL. (Interim Report on the Investigations carried out at the Steelworks of the Ougrée-Marihaye Company.) By Dr. L. BARADUC-MULLER (Paris) 216

I. General equipment of the laboratory 216
II. Recording instruments 217
III. Appliances for creating a vacuum above the steel 217
IV. Measuring appliances for the gaseous volumes extracted from the steel 218
V. Method of operation 218
VI. Analyses 221
VII. Mechanical tests 222
VIII. Micrographic results 222
IX. Details of the experiments 222
X. Mechanical tests 228
XI. Criticisms of the experiments 229

AN EXAMINATION OF FIRE-BRICKS AND SOME OTHER TECHNICAL REFRACTORY MATERIALS. By W. HAMILTON PATTERSON (Birkenhead) 231

Chemical analysis 232
Silica 233
Alumina, ferric oxide, titanium oxide, etc. 233

PAGE
Limit of refractoriness 235
Electric furnace 235
Measurement of temperature 236
Ultimate analysis 239

LIST OF PLATES.

Plates I. to X. Diagrams illustrating Mr. Apfelstedt's Report *To face page* 64
„ XI. „ XIII. Tables illustrating Mr. Rudeloff's Report . „ „ 208

METHODS OF TRANSPORT OF RAW MATERIAL IN THE IRON INDUSTRY

WITH SPECIAL REFERENCE TO THE COST OF PRODUCTION OF PIG IRON.[1]

By J. F. APFELSTEDT (Dresden).

During the last decade the iron industry has made rapid strides, thanks to advancement of experience and knowledge. The world's production of pig iron in 1911 amounted to about 65,859,000 tons, as against 43,380,000 tons in 1902. Table I.

Table I.—*Production of Pig Iron, Iron Ore, Coal, and Coke in Years* 1902 *and* 1912. *In Thousands of Tons.*

Country.	Production of Pig Iron.		Iron Ore Mining.		Coal Mining.		Production of Coke.	
	1902.	**1912.**	**1902.**	**1912.**	**1902.**	**1912.**	**1902.**	**1912.**
Great Britain	8,889	9,006	13,426	13,793	223,415	256,456	?	?
Germany	8,270	17,587	17,677	30,526	103,640	171,073	9,043	28,189
France	2,367	4,785	4,925	18,208	29,114	39,265[3]	1,702	2,420
Russia	2,556	4,130	3,863	8,078	15,954	27,933	1,783	?
Spain	326	65	7,770	9,133	2,643	3,826	392	490
Belgium	1,052	2,262	163	165	22,155	21,909	1,980	3,140
Sweden	523	678	2,795	6,488	295	351	...	...
Austria	1,407[2]	...	3,208[2]	4,810[2]	10,905	15,088	1,122	2,250
Italy	30	373	231	542	410	490	18	430
Greece	...	...	547	...	8	...	...	...
U.S.A.	17,821	29,770	35,554	56,002	255,905	491,090	22,301	47,600
Canada	320	1,015	350	172	6,309	13,151	440	1,259
Newfoundland	...	...	731	...	...	...	...	...
India	...	...	85	...	7,000	14,650	...	...
Japan	...	60	69	78	9,702	19,639	...	...
Algeria	...	...	508	1,153	...	...	...	...
Tunis	...	...	...	...	...	...	...	...

shows the extent to which the various countries participated in this production. The same table also shows the output

[1] Received March 5, 1914. [2] Austria-Hungary. [3] Anthracite included.

of iron ore and of coal in the various countries, together with the production of coke in the same years; while Diagrams I. to IV. show the fluctuations in output and production during this period.

Industrial competition in all countries tends specially towards the reduction of the costs of production, not only as regards the installations directly concerned with the production, but also those indirectly connected with it. The question of the transport of material has become of increasing importance, and efforts are continually directed towards the reduction of these charges.

In considering transport and its influence on the production of iron, a distinction must be made between raw materials, semi-manufactured, and completely manufactured products, all of which bear upon the question of long-distance transport by land and water, of handling, and of local transit between the various parts of the works. To the above products we must add the by-products, since provision must be made for their conveyance also.

A different standpoint must, of course, be taken for each class of goods to be transported, when considering the constructional details of the means of transport to be provided. The value of the material to be transported is of considerable importance in connection with the economical working of a transporter plant. The question of transport requires to be far more carefully worked out in the case of raw materials and by-products than in the case of semi-manufactured and manufactured products.

The Supply of Raw Material.

One of the most important points to consider in planning a metallurgical works is the provision of raw material, together with the possibility of conveying the products.

The possibility of using raw material economically is governed by the cost of production of the iron products which obtains locally, together with the price of the raw material at the place of consumption. This latter amount is appreciably higher than the sale price, that is, the price at the

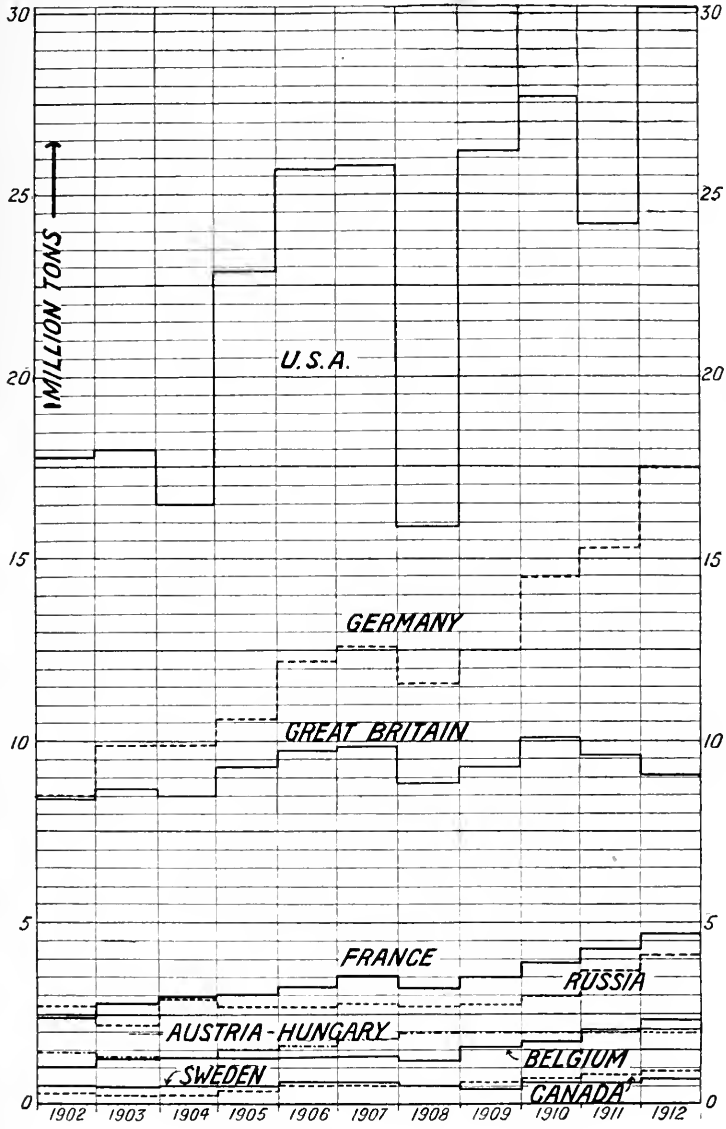


DIAGRAM I.—Pig Iron Production in 1902–1912.

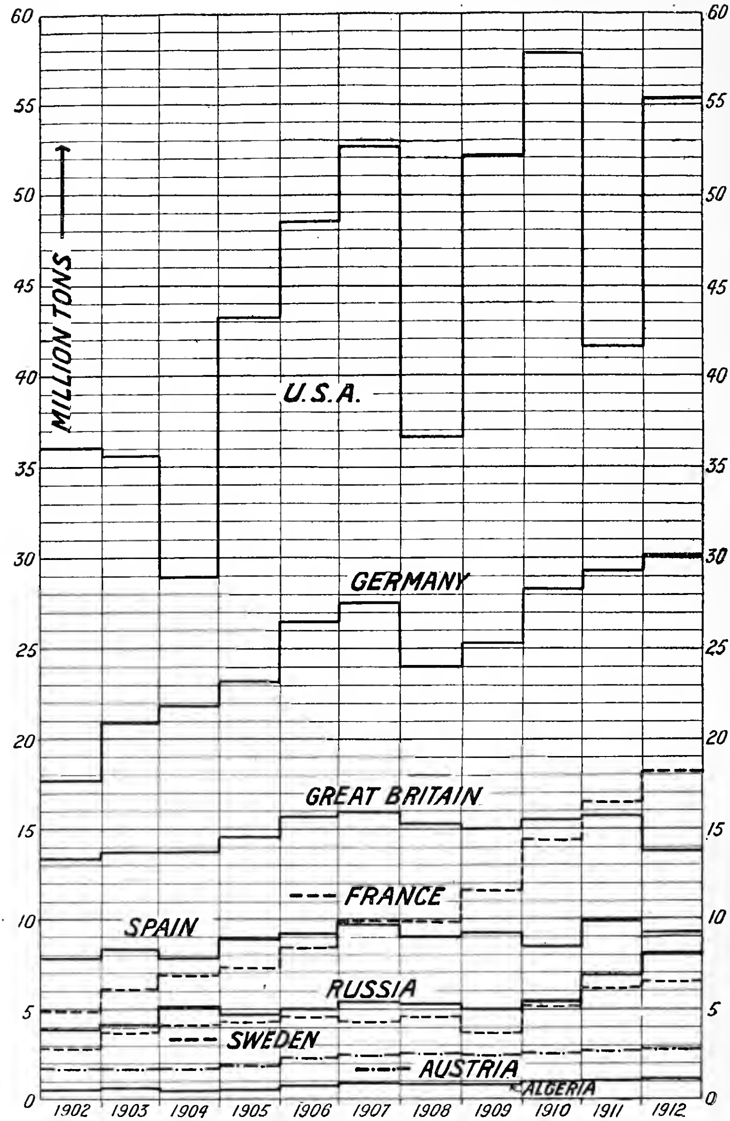


DIAGRAM II.—Output of Iron Ore in 1902–1912.

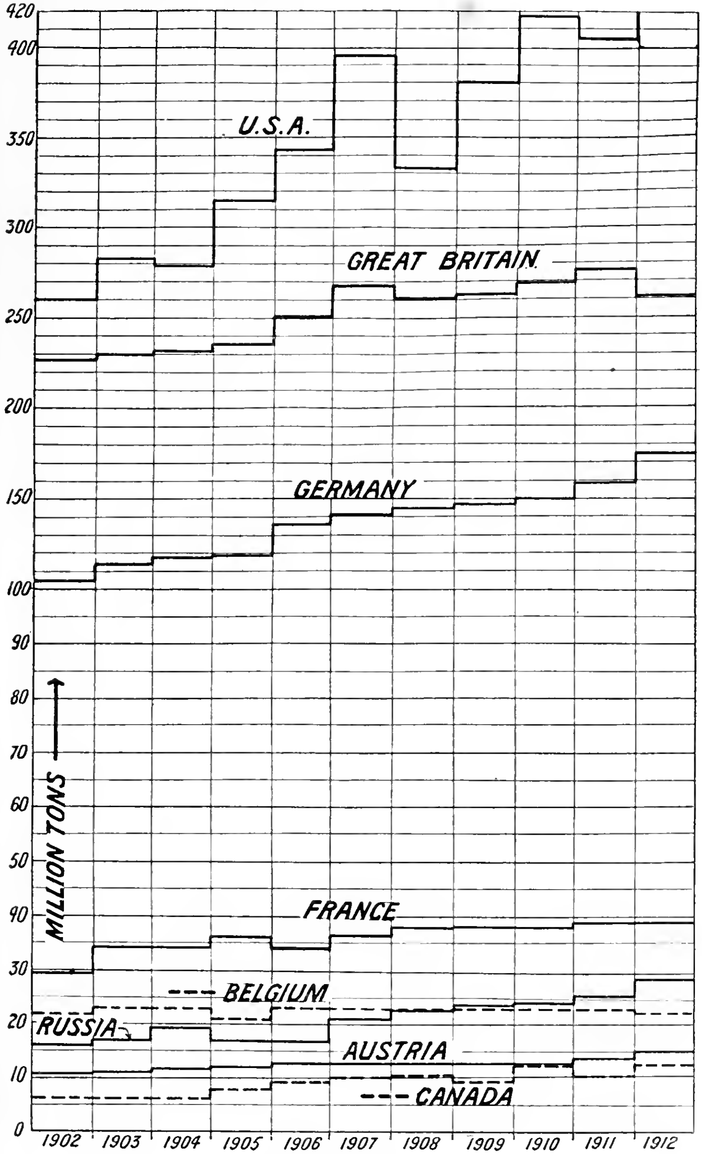


DIAGRAM III.—Output of Coal in 1902–1912.

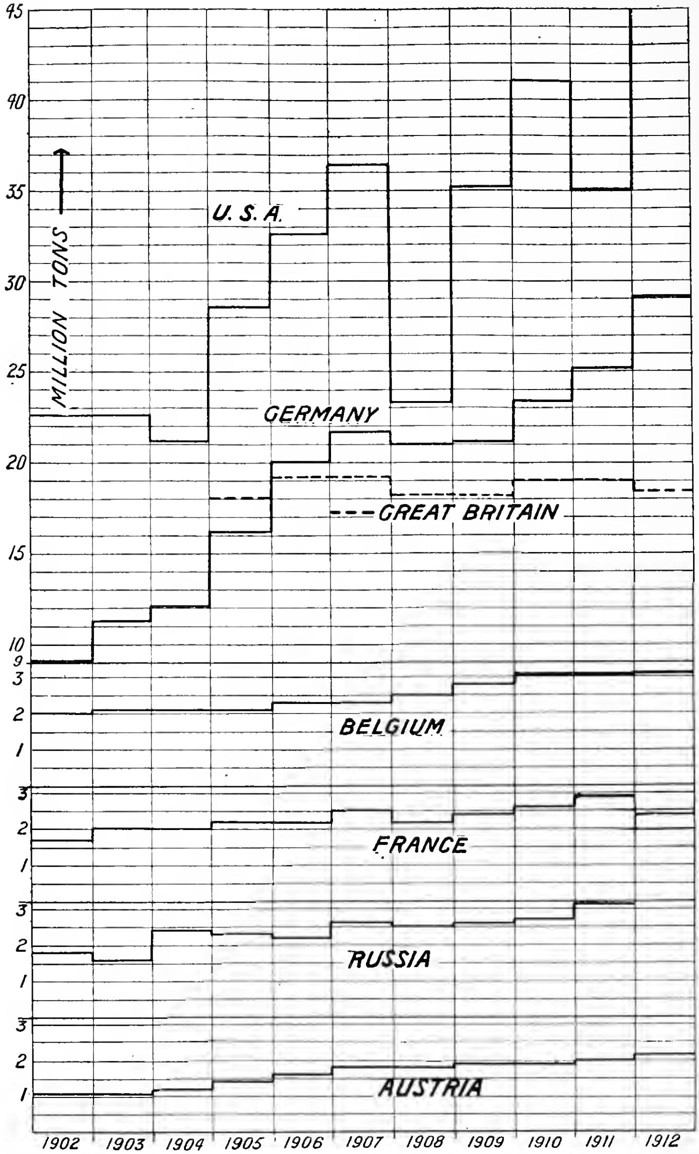


DIAGRAM IV.—Coke Production in 1902–1912.

place of production, owing to transit charges. On account of the low actual value of the raw materials themselves, the transport charges may form an essential part of the price of raw material, and may determine whether it is economical or not to use a certain raw material.

The technical utility of the materials, which determines whether they are worth transporting, depends upon whether they are required for smelting a product of a definite quality. In England, where, in particular, non-phosphoric ores are employed, the phosphoric ores of Sweden have not the same economical value as they have for Germany, which has specialised in the smelting of ores rich in phosphorus.

Let us assume that a ton of pig iron has to be delivered at the points of production A, B, and C for £4. The ore costs at the mine £1; freight for the ore to place A, 100 miles distant, 4*s.*; to B, 300 miles distant, 8*s.*; and to C, 500 miles distant, 12*s.* Thus at point A the ore has increased in price 20 per cent., at B by 40 per cent., and at C by 60 per cent. above the cost at the mine. The increase of price owing to freightage will thus have a great influence on the question as to whether the material is worth transporting, and will only under certain conditions admit of its being economically employed at localities A, B, and C.

On the other hand, it is possible by the provision of means of transport to render it worth while to transport raw materials which are not, in view of their technical importance, capable of standing heavy transit charges, and to render such materials available for the industry.

The Conditions Governing the Situation of an Iron Industry.

The locality of the pig-iron industry is determined by the occurrence of coal and iron. The steel industry, so far as it deals with pure operations independent of the blast-furnace, seeks its locality where coal and scrap may be had cheaply.

In England, coal and ore occur fairly close together, and the ores imported by sea have only short journeys to make

from the ports to the place of consumption. The sea transport and the short land journey (circumstances favouring the cheap supply of the materials) may be said to be the reason why transport plants, and especially those concerning the handling and transport of the raw materials to the blast-furnace, have not developed in England to the same extent as in America and Germany.

The ratio of freight charges to the cost of production is, for England, 8 to 10 per cent., while in some regions of Germany it is as much as 28 to 30 per cent.[1]

Belgium also shares the advantage of cheap long-distance transport, thanks to its excellent situation. Easily navigable rivers, and a highly developed system of canals, tend to keep low the cost of long-distance transport. The fact that Belgium's production of iron considerably exceeds its own requirements affords ample proof that this country takes advantage of cheap transit, although, as a country, she is rich in coal and poor in ores.

The long-distance transport conditions in Germany and France have not kept pace with the development of their industries. The main iron-producing regions of France are situated far away from the sea, near the German frontier. Ores change hands between the two countries, and France obtains a great deal of coal from Germany; but, since these materials must be transported by railway, they are burdened with very heavy freight expenses.

The considerable ore and coal deposits in West and South-west Germany have caused the iron industry to concentrate in this region. By a system of canals, connection is secured with the natural inlet and outlet—the Rhine—while, on the other hand, it is more or less independent of foreign sources of supply. A dense network of railways covers the area, but owing to the high freights the tendency is towards further canals. The advantage of these waterways as a cheap means of inlet and outlet has had the effect of calling into existence a number of ironworks on the North Sea and Baltic Sea coasts. The ironworks in the coal regions of the East, the ore

1 "Gemeinfassliche Darstellung des Eisenhüttenwesens"; *Verein Deutscher Eisenhüttenleute*, Düsseldorf.

for which is nearly all transported by railway, can only compete at a disadvantage on account of the heavy freights.

While the complete absence of coal in Sweden (so rich in valuable ores) is a hindrance to the establishment of an active iron industry, yet her favourable position as an outlet gives her the important position she now holds in regard to supplying other countries with iron ores.

Russia is rich in ores and coal; but as these minerals occur so far apart, it is only by cheap transport that it would be possible to utilise these resources in a competitive manner. The development of the pig-iron industry during the last few years is mainly due to the construction of new railways. The manganese ores of the Caucasus, owing to their favourable situation on the coast, enjoy the advantages of a cheap export.

Spain also suffers from lack of transport facilities, and thus the rich ore-resources of the coastal regions have not enabled the country itself to assume an important position among the iron-producing countries. However, the position of the ore deposits on the coast enables Spain to take an important position among the ore-exporting countries. The prominent position occupied by the United States among the iron-producing countries is due very largely to the presence of good ores and excellent coal, although situated at a great distance apart. Owing to the large quantities of ore to be dealt with, the transport facilities (both long distance and local) have been established on a greater scale here than in any other country. The ores imported into the United States come from Spain and Sweden, and are required by the works situated along the East coast, which are precluded from using American ores from inland owing to the railway freight charges. For the same reason the Swedish and Spanish ores scarcely ever pass beyond the coastal regions.

Import and Export of Raw Material.

As the individual countries are more or less interdependent as regards raw material requirements, the yearly imports and exports are very large (see Table II.).

TABLE II.—*Imports and Exports of the Different Countries in Year* 1912. *In Thousands of Tons.*

Country.	Iron Ore.	Coal.	Coke.	
Great Britain	6,602	1,918		Import
	6,252	64,445	1,011	Export
Germany	11,930	10,020	573	Import
	2,273	30,100	5,664	Export
France	1,404	15,452	2,701	Import
	8,777	1,852	209	Export
Russia	...	5,320	768	Import
	...	208		Export
Spain	...	2,249	344	Import
	8,177	6,496	480	Export
Belgium	6,220	7,854	928	Import
	670	4,901	985	Export
Sweden	...	...	...	Import
	5,420	...	...	Export
Italy	28	...	...	Import
	...	...	...	Export
Austria	662	12,450	887	Import
	144	589	290	Export
U.S.A.	2,104	1,610	110	Import
	1,186	18,148	814	Export
Canada	2,019	14,618	628	Import
	118	...	376	Export

This table shows that the principal importing countries are Germany, England, and Belgium, and the exporting countries Spain, Sweden, and Algeria. It is not possible, however, to determine alone from the statistics of imported and exported ores the significance of the quantities of ore as compared with the pig-iron production of any country, unless account is taken of the value of the ore as defined by the percentage of iron.

England's own Ore Yield and Quantity Imported in 1912.

	Tons.
Ore mined	13,793,000
Exported	6,140,000
Available for own use	7,653,000
Imported from Spain	4,130,000
,, ,, Sweden (estimated)	750,000
,, ,, other countries	1,722,000
Total ore supply	14,255,000

Countries Contributing to England's Supply.

	Per Cent.
England	53·6
Spain	29·0
Sweden	5·3
Other countries	12·1

Average of Iron Extracted from the Ore.

	Per Cent.
England	40
Spain	50
Sweden	62

Pig Iron Produced from Ore Mined and Imported.

	Tons.
England	3,061,200
Spain	2,065,000
Sweden	465,000

England's pig-iron production in 1912 . . 9,006,000 tons

Countries Contributing to above.

	Per Cent.
England	30·6
Spain	23·0
Sweden	5·1

Germany's own Ore Yield and Quantity Exported.

	Tons.
Ore mined	30,526,000
Exported	2,273,000
Available for own use	28,253,000
Imported from Sweden	3,810,000
,, ,, Spain	3,700,000
,, ,, France	2,650,000
,, ,, Russia	644,000
,, ,, Algeria	408,000
,, ,, other countries	718,000
Total ore supply	40,183,000

Countries Contributing to Germany's Supply.

	Per Cent.
Germany	70·4
Sweden	9·4
Spain	9·2
France	6·6
Russia	1·6
Algeria	1·0
Other countries	1·8

Average of Iron Extracted from the Ore.

	Per Cent.
Germany	$33\frac{1}{3}$
Sweden	62
Spain	50
France	30
Russia	45
Algeria	53

Pig Iron Produced from Ore Mined and Imported.

	Tons.
Germany	9,420,000
Sweden	2,360,000
Spain	1,850,000
France	795,000
Russia	299,000
Algeria	216,000
Total	14,940,000

Germany's pig-iron production in 1912 . . . . . 17,587,000 tons.

Countries Contributing to above.

	Per Cent.
Germany	53·6
Sweden	13·4
Spain	10·5
France	4·5
Russia	1·7
Algeria	1·2

Nature of Raw Materials to be Considered in the Provision of Transport Facilities.

The raw materials employed in the production of pig iron in the blast-furnace are as follows:—

Iron and manganese ores, purple ores, slag containing iron, iron scrap; limestone, and slags as fluxes; coke and coal as fuel. The following by-products must also be considered: blast-furnace slag in a liquid or granulated state, and dust from blast-furnace gases. See Table III. and Table IV.

With regard to their aspect as materials of transport, they are easy to handle, can be tipped and shovelled, and are suitable for handling with automatic grabs, self-emptying devices, elevators, belt conveyors, screw conveyors, &c. In places where the material has to slide over inclined surfaces, the angle of inclination should be between 35° and 40°. Very wet coal and wet friable ore require tilting angles of 55°. Where whole wagons are tipped it is desirable when dealing with pulverulent substances to cover the bottom with a thin layer of the material of granular consistency, *e.g.* a thin layer of nut coal should be spread under coal washings. As a general rule, great heights of fall should be avoided in order to prevent breakage of the material and the formation of dust.

TABLE III.—*Weights and Volumes of some Raw Materials.*

	Weight of 1 Cubic Metre. Kilogrammes.	1 Ton contains Cubic Metre.
Brown iron ore (Russia, Upper Silesia)	1350	0·74
German and French minette	1500	0·67
Hæmatite (Germany, England); Claystone, blackband (England); Brown iron ore (Dill and Lahn district); Roasted spathic ore (Germany)	1800	0·56
Brown iron ore (Bilbao); Manganese ores (Caucasus); Unroasted spathic ore (Germany); Roasted spathic ore (Bilbao)	2100	0·48
Hæmatite (Krivoi Rog district)	2500	0·4
Magnetite (Germany)	3000	0·33
Magnetite (Sweden)	3500	0·29
Purple ore	1600	0·62
Blast-furnace dust	1300	0·77
Lump coal	900	1·11
Dry-crushed coking coal	600	1·7
Coke	500	2·0
Congealed blast-furnace slag	2200	0·45
Granulated blast-furnace slag	800	1·25
Tap cinder	2000	0·5
Lime	1400	0·71

TABLE IV.—*Weight of Volume of Ore and Blast-Furnace Dust Briquettes.*[1]

	Shape.	Weight.	Volume.
	Millimetres.	Grammes.	Cubic Centimetres.
Blast-furnace dust—German	Cylindrical, 180 diameter × 113	7340	2885
Blast-furnace dust—American	Cylindrical, 180 diameter × 105	6905	2758
Blast-furnace dust	Bricks, 65 × 120 × 250	4230	1950
Blast-furnace dust	Bricks, 65 × 120 × 88	1525	636
Magnetite I.	Cylindrical, 180 diameter × 105	8890	2656
Magnetite II.	Cylindrical, 180 diameter × 84	7120	2529
Purple ore	Cylindrical, 180 diameter × 110	6990	2783

[1] *Stahl und Eisen*, 1913, No. 38.

The height of fall in charging and discharging is determined by the strength of the material and the nature of the receptacle. The hardest ore is Swedish magnetite iron ore, which does not crumble, and has a crushing strength of 200 to 300 kilogrammes per square centimetre. The standard grabs are not quite suitable for this type of ore, the hard pieces often preventing the closing of the grab. Spathic iron ores when roasted are less crumbly (70 kilogrammes per square centimetre crushing strength), but undergo a decrease in weight up to 30 per cent. In the calcined state, however, they have a tendency to form more dust. Minette in lumps is fairly strong, and crumbles but little. A good deal of dust, however, is formed in mining, and this should be taken into account when storing in bunkers. The Caucasian manganese ores, although of great weight, are very liable to form dust, and thus require grabs which close tightly; the same remark applies to dust from blast-furnace gas.

Ore briquettes and those made from furnace-gas dust are as a rule tipped. Piling them enables more complete utilisation of space, but requires a great deal of time and labour, as in most cases the operation must be done by hand.

The lifting of ores by magnets has not hitherto proved to be economical. The gripping capacity of the magnet is too small in relation to its own weight and the current consumed. A hoisting magnet, made by the Witton-Kramer Electric Hoist and Tool Company, having a diameter of 1300 millimetres, weighs 2500 kilogrammes, and lifts about 800 kilogrammes of ore, *i.e.* it lifts only one-third of its own weight.

Coal and coke require specially careful handling in transport. Both materials are very friable and show a tendency to form slack, which renders difficult the mechanical operations in storing and loading. The formation of slack prevents the loose heaping of the tipped coal, and hinders cooling internally, thus accelerating "weathering." The weathering processes are liable to cause spontaneous combustion if the coal is carried long distances, or is not properly stored in the open; it also suffers in caking capacity, thus lowering the yield in coke and diminishing the crushing resistance. Lump coke should have a crushing strength of 120 to 175 kilo-

grammes per square centimetre, and a piece of normal size should not break when dropped from a height of 2 metres on to a hard surface: Rhenish-Westphalian coke scarcely breaks when dropped from a height of 3 metres. The abrasion of coke during transport from the coke-ovens to the blast-furnace top should not be more than 3 to 4 per cent. Experiments have shown that the losses are: when transhipped once, 0·89 per cent.; twice, 1·74 per cent.; when discharged from railway trucks, 1·43 per cent.; when discharged from railway trucks, through hoppers, by means of a shoot into the ship, 2·69 per cent. In transporting coal and coke, therefore, the height of tip should be as low as possible, and transhipment should be avoided if possible.

Wherever possible, coal should not be stored on the ground, but in bunkers provided with means for ventilation. This method of storing allows free admittance of air and facilitates loading. Where stored on the ground, suitable covering should be provided. If there is much slack, the height of the heaps should not be above 4 metres. A good loading crane should be available to enable the heaps to be removed quickly if there is danger of spontaneous combustion.

Slag in the liquid state should be transported in ladle trucks. The slag is granulated in an iron railway truck (self-discharging type). This method facilitates transport and loading. Granulated slag can be handled by grabs, but requires two to three times as much dumping ground.

Economic Working of Transport Arrangements.

Cheap transit depends on the efficiency of the various transport appliances. Economy of working is attained by utilising to the full the various means of transit, the efficiency of which should satisfy the demands placed upon them. When transport facilities are correctly employed, the working expenses must always be in the same ratio to the unit of efficiency, and such ratio should be as great as possible. The working expenses consist of charges for labour and maintenance costs for the materials necessary for the upkeep of the plant, that is, lubricants, spares, &c. All parts which enhance the value

of a plant should be included in the initial cost and written off with it. Depreciation and working expenses give the prime cost. Whereas in shifting and local transport the prime cost remains invariable within certain limits, this rises and falls, in the case of long-distance transport, by sea and railway, according to transit conditions, which influence the working expenses.

The result of low prime costs is cheap freights. The freights of course largely depend on the prospects of getting return freights, *i.e.* of avoiding the returning of empties. As far as ore is concerned, England enjoys this privilege, coal forming the return freight for ores obtained from Sweden and Spain. Similarly, France has the benefit of this freight on the railways, German and Belgian coal being imported for ores exported to these countries.

Long-distance Transit.

The annual freight charges for the long-distance transport of raw materials exert an influence on the cost of production of iron. In long-distance transport, more importance is attached to cheapness than to rapidity, while in local transport and general transhipment it is cheap and quick conveyance of the goods which is of importance. For long-distance transit, the aim is to secure low charges per ton-mile, and for transhipment and local transport low charges per ton-hour. Whereas on railways the freights are based on class and distance tariffs, the shipping rates are determined by the actual conditions of demand and supply. The arrangement of a sliding scale, providing for a reduction in freights per ton-mile with increasing distance, is the result of a drop in the working expenses for longer distances, since these expenses per mile are reduced with increase in mileage.

Water transport is the cheapest by reason of the greater mobility and the possibility of increasing the capacity of ships so that the ratio of dead load to useful load can be made fairly high. The possible expansion of ships' dimensions—very desirable from the economical point of view, and possible from the technical—is regulated more or less by the dimen-

sions of the principal ports, unless, of course, the latter are of a size to suit ocean-going ships; and by the dimensions of canals and varying depths of rivers in the case of inland navigation.

Ship Transport.

The following are the points to be considered with a view to cheapening the costs of ocean transit:—

Choice of the most suitable size of ship for a particular kind of freight. This depends on the length of the voyage in comparison with the time the ship remains in port, and on the uniformity of nature of the goods to be transported.

The time required for a ship to load and clear is chiefly dependent on the nature and efficiency of the plant provided at the port, which can be the more fully utilised when the holds and hatches of the vessel are also specially adapted. This partly explains the increase in size of the hatches which render it possible to secure uniform stowing even at the edges, obviating trimming by hand, and permitting the accessibility of the loading and discharging devices to the entire hold. Hand stowing is dangerous to the health of the workmen owing to the large amount of dust developed, for which reason alone hand labour should be replaced by mechanical equipment; the same remark applies to the unloading of the cargo.

These considerations have resulted in the evolution of the self-trimming type of ship, which is characterised by sloping bulkheads in the lower part of the ship and by dividing the holds longitudinally with as few cross-bulkheads as possible, and by having a trimming trunk above to provide for the shifting of the cargo. Automatic trimming is also facilitated by making the holds as large as possible and avoiding all stanchions and stringers, the bulkheads being perfectly smooth. Shifting of the cargo is prevented by narrowing the area of a cargo as much as possible athwartships (*cf.* Fig. 1).

Regarding, now, the working costs at sea—for a steamer carrying 5000 tons, these costs are about £30 per day; and for a vessel carrying 10,000 tons, about £50, coal consumption not being included in either case. The maintenance

expenses in the case of vessels of from 5000 to 10,000 tons work out at between 5 to 8 per cent. of their capital value.

The necessity of dispensing with manual labour has further resulted in the development of the automatic unloading steamer, which is independent of the appliances in port and facilitates transhipment to lighters. The advantages of this type of vessel are: (1) a reduction in the number of the crew; (2) more careful treatment of material, since any great height of fall is avoided; (3) freedom from the dust nuisance; (4)

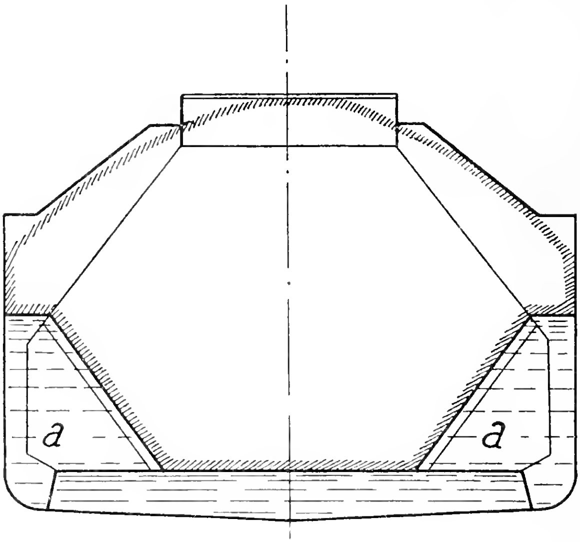


FIG. 1.—Cross Section of Ore-carrying Ship.

prevention of freezing of a wet cargo, by the introduction of numerous heating pipes at the bottom of the holds; (5) preservation of stability and sea-worthiness owing to the comparatively high stowing of the cargo—important in the case of heavy ores.

Plates I. and II. show steamers of the self-discharging type. Plate I.: Self-discharging collier, built by William Doxford and Sons, Ltd., Sunderland (from *Shipbuilding and Shipping Record*, Sept. 4, 1913).

The hull is built on the "single-deck" system, with vertical

frames only, and is fitted with water-ballast tanks. The self-trimming holds have very large hatches; each hold has on both sides, near the bottom, a number of square funnel-shaped openings (*f*), which can be closed by means of sliding doors (*r*). The angle of the sloping sides (about 35°), the absence of horizontal stiffeners, and the smoothness of the sloping floors ensure that the coal, if fairly dry, will slide down to the sides. The bottoms of the holds sloping from the centre of the vessel to the sides provide a tunnel (*a*) on the bottom amidships, which stretches over the entire length of the middle part of the hull.

The unloading equipment of the vessel consists of a pair of endless wire ropes (Doxford's patent) carrying pressed steel buckets mounted on rollers running on angle rails. They are driven by a steam-engine, situated at the after part of the vessel, and spur and bevel gearing. These transporter belts (*s*) are run, one under each of the hopper-shaped apertures of the holds at both sides of the tunnel (*a*), from fore to aft. The conveyor belts are charged through the drop-feed doors (*r*), opened by hand from the tunnel (*a*). The feed-doors are opened successively by the operator and bolted. The bolting arrangement is devised so that only one drop-feed door on both sides of the vessel is open simultaneously. In addition, the doors can also be worked to suit the size of the material. The material picked up by the conveyor belts, after passing a weighing machine, is discharged through shoots (of adjustable incline) into the lighters, &c.

The number of hands required is three men for the engine, two for serving the doors, and two in reserve.

A steamer built for Messrs. Sauber, of Hamburg, has a carrying capacity of 3700 tons, with a draught of 18 feet 9¼ inches. For driving the belt conveyors, a compound steam-engine of 400 horse-power is employed, giving to each belt (about 1 metre wide) a speed of about 80 feet per minute. The amount conveyed per hour is 400 to 1200 tons, according to the size of pieces.

The capital cost of the steamer is about 850,000 marks (£42,500). The working and maintenance costs amount to scarcely ¼*d.* per ton of material conveyed.

The vessel[1] shown on Plate II. is employed in transporting Swedish ores, and is constructed on the Johnson-Welin system.

The steamer *Vollrath Tham*, of the same type, is of 8000 tons burden, and the *Sir Ernest Cassel* of 10,800 tons. They are owned by the Tracfikactiebolaget, Grangesberg-Oxelosund, Stockholm, and were built by Messrs. R. & W. Hawthorne, Leslie & Co., of Hebburn-on-Tyne. The space available for the cargo is divided up by cross-bulkheads, built in so that there are, alternately, holds for the cargo of ore (a), and conveyor shafts (h) for working the cargo. The ore spaces (a) with their self-trimming bottoms have chambers built in, inclined at 42°, which lead to four doors (k) opening laterally to the conveyor shaft (h). The doors can be opened by a workman from the tunnel (z) under the holds. At the side of each unloading hatch (h) are two electric slewing cranes, each serving a tipping conveyor bucket. The suspension and manipulation of the conveyor buckets are so arranged that the bucket, after passing into the shaft (h) in front of the doors (k) is filled when the latter are opened. The door is then closed again, the full skip raised and slewed outwards. The mechanism on the doors is such that the door can always be completely closed, notwithstanding any pieces of ore which may settle in the opening.

The slewing cranes are of ordinary type, with electric drive for lifting and slewing, and are operated from a platform situated fairly high up and permitting a free view over the range of each crane. From this stand the buckets are also tipped by the gear motion of the lifting mechanism. The electric current is supplied from a power-station situated abaft, the same station also supplying the lighting.

The steamer *Vollrath Tham* has ten cranes, each with a lifting capacity of 2500 kilogrammes and a lifting speed of 0·38 metre per second. The *Sir Ernest Cassel* has twelve cranes, each carrying 3500 kilogrammes and having a lifting speed of 0·38 metre per second.

For unloading, the following attendants are required: ten

[1] *Stahl und Eisen*, 1911, No. 38.

or twelve crane-drivers and ten and twelve men respectively for serving the doors.

The ore is loaded into the vessels by means of shoots through the hatches. The holds being fairly narrow they are trimmed automatically to the top.

TABLE V.

Country.	Railway Mileage. Kilometres.		Number of Ships.[1]		Net Tonnage.[2]		Average Net Tonnage.[3]	
	1902.	1911.	1902.	1911.	1902.	1911.	1902.	1911.
Great Britain and Ireland	35,660	37,649	11,041	11,442	10,278	12,083	930	1060
Germany	53,700	61,936	...	...	2,093	2,904	...	...
France	44,654	50,232	1,291	1,478	974	1,322	750	900
Russia and Finland	52,339	61,078	1,295	1,191	588	599	450	500
Spain	13,770	15,097	614	591	525	481	860	820
U.S.A.	325,778	396,860	2,931	2,762	1,976	2,211	675	800
Belgium	6,629	8,660	122	160	116	159	950	1180
Sweden and Norway	14,521	17,187	3,758	3,510	1,809	2,144	480	615
Italy	15,942	17,228	1,223	1,077	909	934	740	870
Greece	1,035	1,590	...	...	...	...	...	...
Austria-Hungary	37,682	44,820	301	382	357	530	1200	1400
Canada	30,358	40,869	...	...	...	...	...	...

RAILWAY TRANSIT.

The conditions governing the rates of tariffs for the transit of raw materials by rail is, in general, independent of the distance from the iron-producing centres. In the interests of the satisfactory development of the industry, it devolves upon the railway companies to provide facilities for cheap transit of raw materials, which in this case is also attained by reducing the working expenses. Of the European railways, about 60 per cent. are State-owned; England and the United States have private systems.

For transporting the raw materials, standard gauge goods wagons are employed (carrying in England up to 12 tons, and in Germany up to 15 tons). To facilitate charging and unloading, these trucks are provided with hinged ends and sides. The advantages of having trucks of low-carrying capacity

[1] Ships with more than 100 registered tons. [2] 1000 registered tons. [3] Registered tons.

consist in their being built short and being easily movable (pushing in works without locomotives). The disadvantages of such wagons are the unfavourable ratio of net load to tare, and of the stowage room to the length of the truck, so that the cost of hauling the empty train is disproportionately heavy. Moreover, the capital cost of the wagons is too high in proportion to the carrying capacity. In order to strengthen the wagons and make them better able to withstand collision, pressed steel frames with wood bodies are used in England for building coal wagons, or, generally, pressed steel plates for the ends and sides, with the bottom of wood. It is not economical for the railways to increase the carrying capacities of standard gauge wagons, unless, of course, they can be used for the regular traffic on special lines and between special areas (as, for example, in the United States, where bulk goods of the same class—coal and ore—and in equal quantities, are carried over great distances); neither is this increase advantageous from the consignee's point of view, as the cost of unloading such large wagons would be increased.

The advantages arising from the use of wagons of large carrying capacity are to be found in the attainment of low working expenses in relation to the weight-unit of the goods transported, as the ratio of net load to tare of the wagon increases with increasing size; the consumption of power for working the empty wagons, and the working and maintenance expenses, and the capital cost per ton of goods transported, are reduced. Owing to the shorter train lengths resulting from the comparatively shorter overall length of the trucks, the shunting operations are simplified and greater safety in working is attained (less braking required). As was stated above, however, it is the question of loading and unloading which is the deciding factor in the adoption or otherwise of standard gauge wagons of large carrying capacity. Unless they can be quickly unloaded, considerable rolling stock is necessary, and its rapid circulation is prevented, causing high running costs, and, consequently, high transit freights. Their use, however, renders it possible to employ the standard railway plant, tippers and cranes being used for unloading purposes.

STORAGE OF RAW MATERIALS.

The raw materials are stored in pits, on the level, and in bunkers.

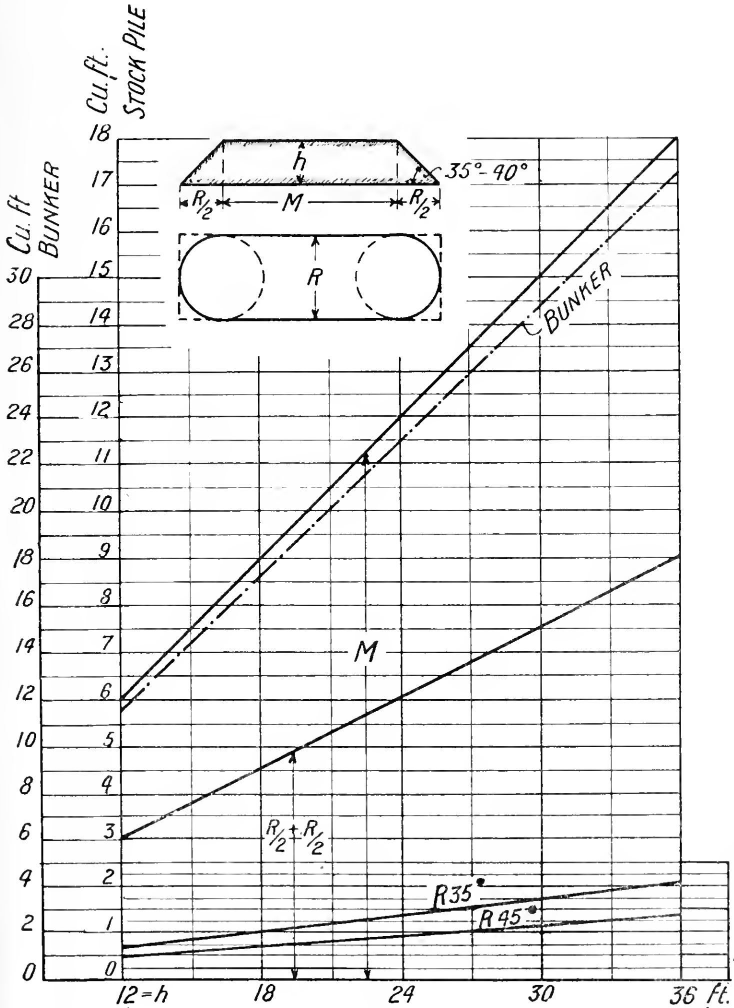


DIAGRAM V.—Relation of Cubic Contents of Stock Pile to Area of Base.

The pits are generally only employed with stationary tips. They necessitate the use of hoists for loading into the trucks, &c. These transhipping devices, however, require pits at least 35 feet deep. The cost under this head depends on the nature of the ground, being particularly high if the pit is sunk to the ground water level. The costs may amount to £1500. Pits afford no protection against the freezing of the material.

In order economically to use the storage grounds on the level, the material is stored to a height of 36 feet; coal, however, forms an exception, for the reasons already stated, and should not be stacked above 13 feet. Diagram V. shows the useful capacity, in cubic feet, of a loosely heaped stock for a ground area of 12 to 36 square feet. The breadth of room required is dependent on the angle of repose of the material (35° to 45°). In order more efficiently to utilise the storage ground, and to secure more careful storage, the stock yard should be enclosed on three sides with masonry (concrete), the ground being paved with blast-furnace slag. The wall-thickness depends on the capacity of the natural bunker thus formed. The cost of a cubic yard of concrete is about 12s. The thickness of the cement floor varies between 6 inches and 1 foot, according to the nature of the ground. A cubic yard of slag cement costs about 4s. Elevated tracks are carried above the stock yard for emptying the standard gauge railway wagons, the automatic dischargers, and the travelling tips (where such are employed). The cost of such an elevated track is (according to German conditions)[1]—

Per yard of track (rails and fastening, wood sleepers, planking, laying of rails and sleepers)	59s. 6d.
Per 1 ton of ironwork of bridges, according to span	£14 to £15, 5s.
Per 1 cubic yard of masonry pier	12s. 0d.

Diagram VI. shows the total cost of 1 yard of elevated railway on masonry piers, with a distance between the piers of 26 to 46 feet, and assuming a height above ground of 13 to 40 feet:—

E_{26}, E_{32}, E_{40}, E_{46}.—Costs for the ironwork of the crane track, including permanent way material for pitches between piers of 26, 32, 40, and 46 feet.

P_{26}, P_{32}, P_{40}, P_{46}.—Costs for piers with pitches of 26, 32, 40, and 46 feet.

[1] Lilge, *Hochofenbegichtungsanlagen.*

The storage bunkers for coke and ore are constructed of ferro-concrete (Figs. 2*a* and 2*b*), or of ironwork (Figs. 3*a* and 3*b*). In cases where the works can construct the ironwork

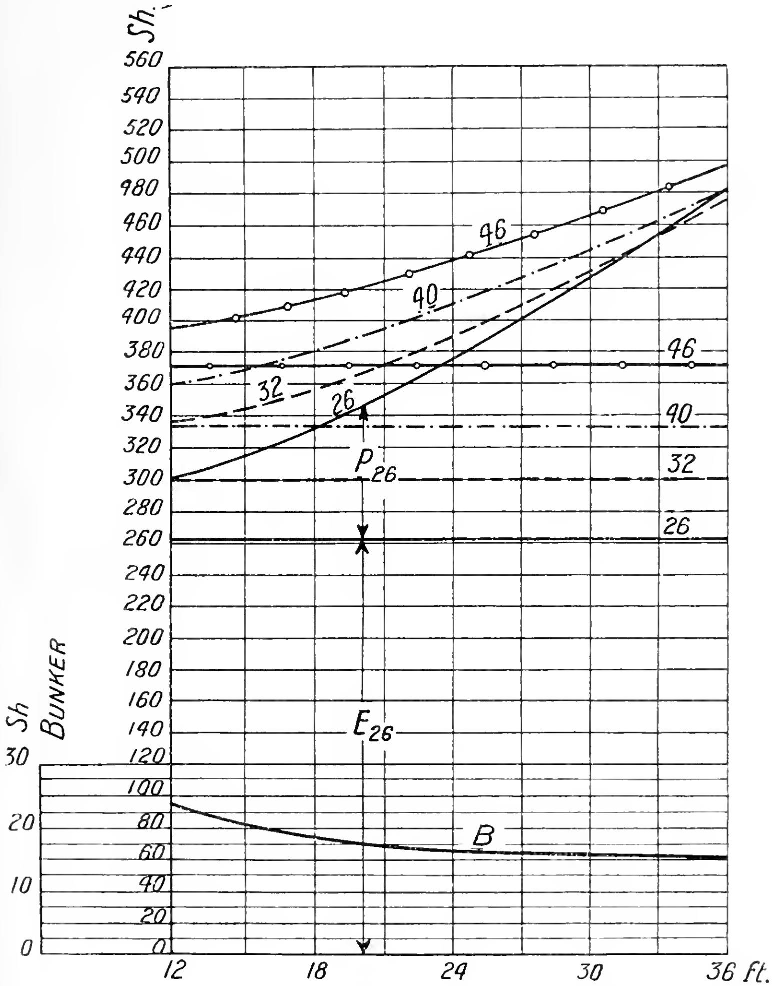


DIAGRAM VI.—Capital Cost per Yard of Overhead Track on Masonry Piers.

themselves, the cost of the iron bunkers is generally lower than those constructed of ferro-concrete. Bunkers constructed on the "Berquist" system (Figs. 3*a* and 3*b*) have the hoppers

built of iron plates in the form of a catenary curve. Since in this case the material is only under tensile stress, the plates need not be of great thickness (about $\frac{3}{8}$ inch to $\frac{5}{8}$ inch). The advantages of the Berquist bunkers over the ferro-concrete are that the ore, even when wet and fine, shakes down well, as the walls are smooth and remain so, which is not the case with ferro-concrete, further, they are more durable, their construction is not hindered by weather conditions, and if replaced the material has a scrap value.

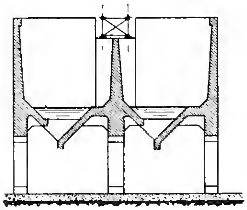


FIG. 2*a*.

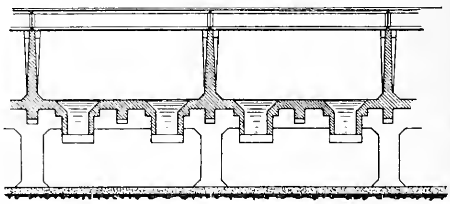


FIG. 2*b*.

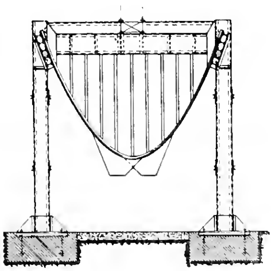


FIG. 3*a*.

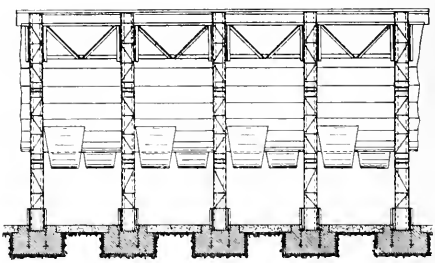


FIG. 3*b*.

SECTIONAL VIEWS OF CONCRETE AND STEEL BUNKERS.

The advantage of ferro-concrete bunkers lies in their simple construction; maintenance costs are obviated, while in the case of ironwork such expenses are high.

It is possible with both types of bunkers to prevent the stock from freezing by fitting double walls in the lower part of the bunker and fixing heating pipes.

The dash-dot line in Diagram V. shows the useful capacity in cubic feet per square feet of ground area when employing ferro-concrete ore bunkers, according to the costs given in

curve "B," Diagram VI. (without overhead track or bunker cover). Curve "B" represents the total cost in shillings of ferro-concrete ore bunkers with a useful height of 12 to 36 feet (per cubic yard of useful capacity).

The bunkers are arranged in parallel and in series on iron or masonry pillars, the arrangement being governed according to whether the bunkers are used for various ores, coke, or limestone, and according to the way in which they are subsequently drawn off and distributed, The bunkers are emptied through trap-doors of simple pattern (Helm trap-doors costing about £7, 10s. each) or a more complicated pattern (Züblin door, £65 each), according to whether more or less importance is attached to the exactness of the quantity removed.

When the raw material is carried by water to the blast-furnaces, and transit is temporarily interrupted by freezing, it is necessary to stock a large quantity of raw materials. It is preferable in this case, for the sake of economy, to store on the level.

Unloading the Railway Wagons.

When dealing with the question of the unloading of railway wagons, a distinction should be made as to whether the work of unloading is to proceed simultaneously with the work of distribution, or whether the arrangements for discharging and distributing the material are to be worked separately. In the latter case, the apparatus mostly employed are automatic dischargers and wagon-tips.

Automatic Unloaders.

In addition to the almost absolute exclusion of manual labour, the economic advantage of automatic unloaders consists in the increase in the ton-mileage by increasing the circulation of the wagons as a result of quick unloading. The attainment of this advantage requires, however, that the place where the loading and unloading operations are carried on should be adapted to the type of the automatic unloader employed, all unnecessary shunting being avoided so as to delay the wagons

as little as possible. The automatic unloader takes up the material from bunkers at a higher level, and passes it on to those at a lower level. Where, in the latter instance, pits are not employed, the train will always have to be drawn up a gradient. This arrangement of bunkers and pits is very expensive. Where transport and consumption are not vested in the same hands, *i.e.* where the ironworks only indirectly enjoys the benefit of working with auto unloaders (this advantage consisting in a reduction of freight), then the deciding factor for the consumer is the initial cost—especially as regards the reconstruction of old works—in view of economy of working.

The gross weight of the wagons in ordinary traffic is limited by the maximum permissible wheel pressure, which depends on the strength of the permanent way. In England this wheel pressure is from 9 to 10 tons, in Germany up to 9 tons, and in the United States 11 to 12 tons. Wagons carrying over 20 tons must, therefore, generally have four axles. Two 20-ton wagons weigh, of course, about as much as one 40-ton wagon, and cost just as much; on the other hand, one 40-ton wagon is almost 3 metres shorter than the two 20-ton trucks.

There are special sizes of truck for special materials. A 20-ton ore wagon will not hold more than 12 tons of coke; and a coal wagon carrying 20 tons will only contain 15 tons of coke. The wagons must be filled with material corresponding to the required dead-weight, so that the gross weight bears the right proportion to the permissible wheel pressure. Wagons having too large a holding capacity in proportion to the load, have too great a tare and are too long. Referred to the useful load per ton, a wagon correctly dimensioned is cheaper.

The most general type of automatic unloader has a body of rectangular cross-section. In the lower part of the sloping walls formed in this manner there are trap-doors opening outwards under the weight of the goods, or downwards in the case of discharging through the bottom. Figs. 4–8 show some cross-sections of automatic unloaders (Talbot type, built by Gust, Talbot & Co., Aix-la-Chapelle) discharging either from one side or the other, or simultaneously from both sides, or in

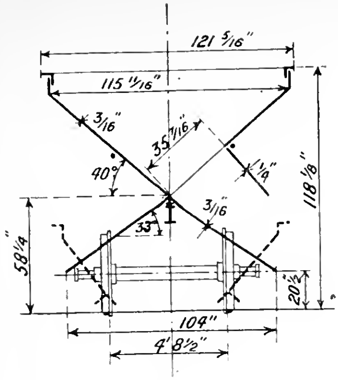


FIG. 4.
Capacity: 16,800 kilogrammes.
29·8 cubic yards.

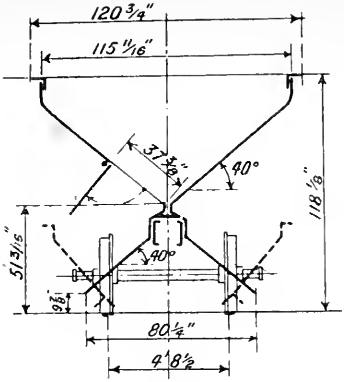


FIG. 5.
Capacity: 20,000 kilogrammes.
19·7 cubic yards.

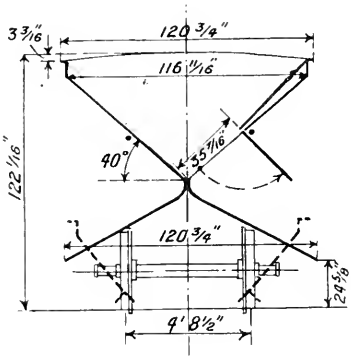


FIG. 6.
Capacity: 30,000 kilogrammes.
19 cubic yards.

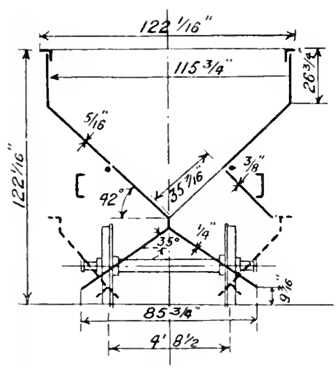


FIG. 7.
Capacity: 40,000 kilogrammes.
26·9 cubic yards.

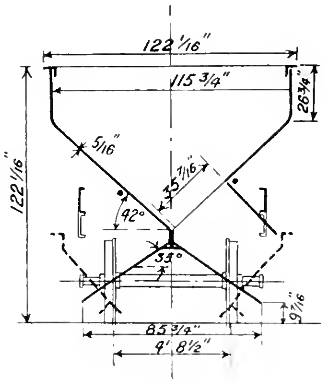


FIG. 8.
Capacity: 40,000 kilogrammes.
35·8 cubic yards.

AUTOMATIC DISCHARGER. TALBOT SYSTEM.

special constructions discharging between the rails. Table VI. gives a comparative summary of wagons intended for bulk transit.

Costs of Employing Automatic Unloaders as against those Incurred when Using Ordinary Wagons.

Let us suppose that it is desired to bring from an ore mine, twenty-five miles distant, a daily quantity of 1500 tons of ore to the blast-furnaces.

The following are necessary for the above:—

1. One hundred standard gauge wagons, each carrying 15 tons, loaded from bunkers, and discharged by hand into bunkers situated below an elevated railway, or into a store. Transport is effected in two separate trains, each made up of fifty wagons. The outward and return journeys take three hours; and the time necessary for loading and unloading is twenty-one hours. Or,

2. Nineteen automatic dischargers, each of 40 tons carrying capacity, loaded from bunkers and unloaded from an elevated railway. The train of nineteen wagons makes two journeys in twenty-four hours.

With regard to 1:

An ordinary 15-ton wagon (without brakes) for 4 feet $8\frac{1}{2}$ inches gauge weighs 8000 kilogrammes, and costs £140.

Standing charges (interest and depreciation) may be taken as 15 per cent. of the initial cost.

Cost of transport, 0·2d. per ton mile.

The transit costs are made up of wages and cost of material necessary for locomotive and wagons, for maintenance and repairs to the train and permanent way, and for shunting and supervision.

Cost of unloading, $1\frac{1}{2}$d. per ton of material.

The material is ejected through the side doors of the truck. Unloading takes up the time of two workmen for two to three hours, according to the condition of the material (whether dry or wet, or in large or small pieces).

TABLE VI.—*Railway Wagons.*

Type (all with Brakes).	Country or Makers.	Application.	Net Load in Tons.	Tare in Tons.	Capacity in Cubic Metres.	$a:b$.	Length between Buffers in Metres.	$c:d$.	Approximate cost in Shillings.
			a.	*b*.	*c*.		*d*.		
Standard open goods wagon	Germany	Goods in bulk	15·0	8·4	18·0	1·78	8·5	2·12	3100
,, ,,	Austria	,,	15·0	8·1	20·6	1·85	10·12	2·02	...
Wooden wagon with hopper-shaped body	England	,,	...	8·9	9·7	...	...	...	...
Iron wagon with opening sides	Germany	Coal	15·0	8·47	19·0	1·77	6·95	2·74	3000
,, ,,	,,	,,	20·0	8·4	26·0	2·37	8·0	3·25	...
Standard wagons with doors	,,	Coke	15·0	8·75	36·0	1·93	9·8	3·68	3300
,, ,,	Belgium	,,	10·0	6·1	23·0	1·64	...	3·53	...
,, ,,	Canada	Coal	36·0	16·8	40·0	2·14	...	...	...
,, ,,	South Africa	,,	45·0	18·6	48·0	2·42	13·6	3·53	...
Wagons of pressed plate	...	,,	20·0	9·25	32·7	2·16	8·5	3·85	...
Automatic unloaders	France	Ore	50·0	15·4	28·0	3·24	...	...	...
,, ,,	Austria	,,	20·0	7·7	15·4	2·6	6·24	2·47	...
,, ,,	England	Coal	20·0	8·0	25·0	2·5	6·4	3·9	...
,, ,,	Orenstein and Koppel	,,	40·0	20·6	60·0	1·94	14·15	4·24	...
,, ,, Plate III., Fig. 1	Talbot	,,	16·8	11·25	22·7	1·5	10·0	2·27	4800
,, ,, ,, ,, 2	,,	,,	20·0	10·3	15·0	1·94	7·9	1·9	4200
,, ,, ,, ,, 3	,,	Ore	30·0	13·1	14·5	2·3	8·2	1·77	5200
,, ,, ,, ,, 4	,,	,,	40·0	18·4	20·5	2·17	10·764	1·92	7200
,, ,, ,, ,, 5	,,	,,	40·0	21·3	27·3	1·83	12·45	2·2	8400

With regard to 2:

A 40-ton automatic discharger (with brakes) for the same gauge weighs 18,400 kilogrammes, and costs £370.

Standing charges, 15 per cent.

Cost of transport, 0·16d. per ton-mile.

This amount is smaller when compared with the cost of ordinary wagons, owing to the smaller staff and less shunting required. The proportion for maintenance of permanent way is, in the present case, higher than in 1 owing to the greater weight of the wagons and the heavier wear on curves of small radius.

Cost of unloading, 0·05d. per ton of material.

A period of two minutes only is required for unloading a 40-ton automatic discharger, provided the material shakes down well. Where it has to be assisted by tapping the walls and cleaning the corners, the time is, on the average, ten minutes.

Calculation of Cost of Installation and Working.

1. Tare of train—

	Tons.
$2 \times 100 \times 8000$ kilos	=1575
Useful load	1500
	3075

Ton-miles run—

$$3075 \times 25 = 76,875.$$

Cost of transport, $76,875 \times 0·2$	15,375d.
Cost of unloading, $1,500 \times 1·5$	2,250d.
Daily working expenses	17,625d.

Annual standing charges—

$$100 \times 140 \times 0·15 = £2100.$$

Daily standing charges, $\frac{2100}{300} = £7$	1,680d.
Total daily cost	19,305d.

$$\text{Cost per ton, } \frac{19,305}{1500} = 13\text{d.}$$

2. Tare of train—

	Tons.
$4 \times 19 \times 18,400$ kilos	=1376
Useful load	1500
	2876

Ton-miles run—

$$2876 \times 25 = 71{,}900.$$

Cost of transport, $71{,}900 \times 0{\cdot}16$	11,504d.
Cost of unloading, $1{,}500 \times 0{\cdot}05$	75d.
Daily working expenses	11,579d.

Annual standing charges—

$$19 \times 370 \times 0{\cdot}15 = £1054.$$

Daily standing charges, $\frac{1054}{300} = £3{\cdot}52$	845d.
Total daily cost	12,424d.

$$\text{Cost per ton, } \frac{12{,}424}{1500} = 8{\cdot}3\text{d.}$$

Wagon-tips.

In place of unloading by hand and by automatic dischargers, stationary and portable tips are used for unloading ordinary railway wagons at stations and harbours, and for unloading at the works. The smelting of various types of ores, and the endeavour to effect the preliminary mixing of the charges when storing the ore, have resulted in the introduction of portable tips in place of the stationary type at ironworks. The portable tips are adapted for loading bins from an overhead railway, as well as for storing on level ground up to a height of heap of 1·5 to 2 metres. Plate III. shows a tip of this type (Aumund's patent), built by the Deutsche Maschinenfabrik A.G., Duisburg. The wagon-tip is built so as to be adaptable to the goods trains used in general traffic. The upper carriage, containing a rotating and tipping platform, is supported by means of rollers upon a standard gauge undercarriage. The platform can be tilted to 30° and 45° from the horizontal. Two electric motors are fitted to the undercarriage—one for travelling the tip, and the other for rotating the platform—while the upper carriage contains a motor for bringing the wagon on to the tipping platform, and one for tipping it. When the wagon to be tipped has been lifted up, it assumes an inclination of 30°, which is the tilt of the platform when the tip is in use. The platform is then turned through 90° until at right angles to the rails; the ends of the wagon are open, and the tilt is increased to 45°, so as to discharge the wagon completely. The wagons can be hoisted or lowered from both sides of the tip. Provided the material

settles properly and does not stick, it is possible in one hour to tip from six to eight wagons of 20 tons capacity, even where the wagons have to be fetched a distance of 30 metres.

Diagram VII. is a curve showing the economy resulting from the use of a tip of this kind of 1500 tons = 100 × 15-ton wagon

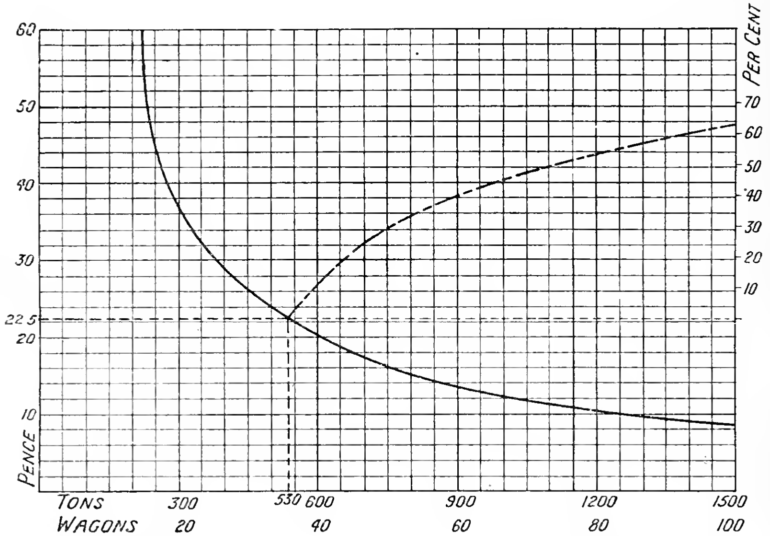


DIAGRAM VII.—Economy of a Portable and Revolvable curved Side-tipper.

daily capacity, handling different materials daily. The curve shows that such a tip, when discharging more than thirty-three wagons daily = about 530 tons, is more economical than unloading by hand at 1·5d. per ton. Another curve shows the increased saving per cent. with increasing number of trucks unloaded, as against unloading by hand. With an extraction from the ore of $33\frac{1}{3}$ per cent. = 500 tons of pig iron, the net cost of unloading per 1 ton of pig iron, employing manual labour, is 4·5d.; using automatic dischargers, 0·15d.; and using wagon-tips, 1·68d.

Unloading from Ships.

For the purposes of unloading from ships having no automatic unloading device, portable slewing cranes and loading

bridges are generally used. Ironworks obtaining their raw material by water are compelled to keep large stocks, as water is not a very suitable means of transport, owing to the varying height of rivers and the freezing up of rivers and canals.

The work of discharging requires devices insuring rapidity of working, so as to reduce to a minimum the time the ship remains in port. Where unloading is carried out by loading bridges, the following points are the most important. It must always be possible to work with two bridges simultaneously in a ship's hatch. If the height of lift and length of travel are short, the carrying capacity of the traveller on the bridge must be correspondingly higher, since nothing is gained by increasing the speed.

Previously, it has only been possible for two loading bridges to be operated simultaneously in a hatchway by the provision of slewing trolleys with jibs, which, owing to their mobility, obviate a too frequent moving of the heavy bridges. The centrifugal force due to the slewing of the cranes necessitates extra strongly built bridges, and prevents the use of high speeds for the slewing of the jibs, and consequently rectilinear motions only are aimed at now instead of the slewing motions.

In order to render it possible to have two bridges side by side working simultaneously in a hatchway, the construction of the individual bridges has been so arranged that the entire bridge can be turned through an angle of about 30° about its farther supporting column at the landward end.

In Plate IV. illustrations are shown of ore and coal loading bridges with automatic grabs, as constructed by the Lauchhammer Company, at Lauchhammer, Saxony.

The bridges load from the vessel direct into bunkers, at a rate of 75 to 95 tons per hour, according to the nature of the material transported. Assuming the travelling crab to carry 5000 kilogrammes, the working speeds and motor horse-powers are as follows:

	Metres per Minute.	Horse-Power.
Hoisting	50	85
Travel of crab	120	15
Travel of legs	20	2×10
Jib-motor		15

The receptacles used for conveying are at present generally automatic grabs and self-emptying skips. In particular, the automatic grab is very well suited for not too hard ores; but for coal and coke it is not so suitable, since it has a tendency to break up the material. Dusty ores require well-closing grabs so as to prevent loss in transhipment. To obtain satisfactory lifting with the grab, the type of grab should be such that the edges of the two halves of the grab when open should be perpendicular on the material. If the material is wet and the edges of the grab not perpendicular, as stated, the grab does not penetrate the material, but closes on it. Special types of grab have been designed for hard ores, as the latter are always difficult to unload by hoisting apparatus, and the ordinary grabs are not adapted to them owing to the large or hard pieces often preventing its closing. These circumstances led to the construction of self-discharging steamers, where the ores are shot into skips. These special types of grab have cutting surfaces made of the best material, and they develop such a high pressure on closing that even the hardest ores are cut up.

The weight of the grabs themselves is, of course, very considerable: the ratio of the useful load to the tare is often 1 : 1. A considerable amount of power is therefore necessary for raising the dead load. On the other hand, however, the tare of the grab considerably facilitates the work of closing and penetrating the material, so that current is saved in this direction. For the latter reason, the equalisation of the weight of the grab by a counterweight is done away with.

Fig. 9 shows a grab of the type under discussion (built by the Lauchhammer Co.), in which the closing force (up to 30 tons) is attained by a chain fitted in the hoisting mechanism. The same result is reached with the toggle joint lever gearing. A motor for closing the grab can be mounted on the grab suspension. Table VII. gives a comparative idea of grabs of various capacities.

The grabs are designed as four-rope grabs, and are driven in conjunction with the hoisting mechanism from the driver's stand built on to the trolley. The grab may be opened or closed when at any height.

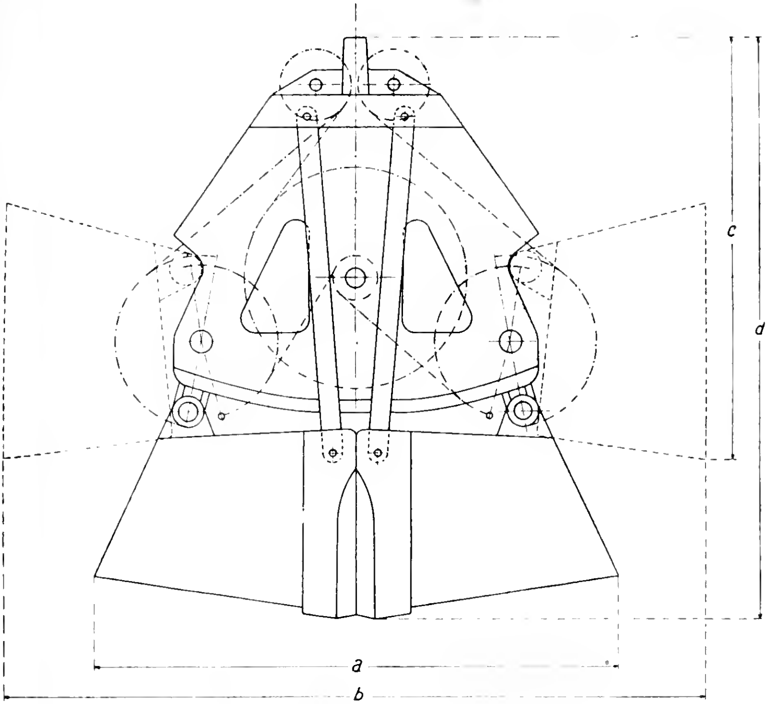


Fig. 9.—Lauchhammer Automatic Grab.

Table VII.—*Automatic Grab (Fig. 9): Capacity, Dimensions, and Weight.*

Capacity.	*a*	*b*	*c*	*d*	Width.	Weight.	Cost.	I.[1]	II.[2]
Cubic Metres.	Inches.	Inches.	Inches.	Inches.	Inches.	Kgs.	Shillings.	Kgs.	
1·0	82¾	106¼	68	88⅝	39⅜	2900	3000	3,500	0·83
1·25	90½	118	72⅞	102⅜	41⅜	3500	3400	4,375	0·8
1·5	96½	129¾	82¾	108¼	43⅜	4600	4500	5,250	0·88
2·0	114	153¼	94½	128	47¼	5800	5600	7,000	0·83
2·5	118	165	102⅜	141¾	51⅛	7500	7400	8,750	0·86
3·0	122	172⅞	110¼	151	51⅛	9000	8700	10,500	0·85

[1] Weight of ore picked up (Swedish magnetite).
[2] Ratio of weight of grab to weight of load.

Two or three men in the ship, in addition to the crane-driver, are necessary to serve the grab, the men in the ship shovelling the material out of the corners of the grab. The type of hold having sloping walls facilitates the working of the grab considerably.

Calculation of Cost of Plant and Working Expenses.

A loading bridge in accordance with Plate IV. should be capable of dealing with 75 tons per hour when the working speeds and motor horse-powers already given are adhered to.

Grab (normal type)—1800 kilogrammes tare: 1·5 cubic metre capacity.
Ore—weight of one cubic metre—2000 kilogrammes.
Useful load with one lift—3000 kilogrammes.
Number of lifts per hour—$\frac{75,000}{3,000} = 25$.

One round of operations with the crane consists of—

	Seconds.
Grabbing the ore	15
Hoisting to 20 metres	20
Trolley travel—40 metres	30
Discharging over bunker	10
Return journey of trolley	20
Lowering and setting the grab	15
Duration of one round of operations	110

As the cargo continually decreases, this time is increased somewhat, since the grab must be adjusted to correspond with the shovelled-up heaps. Moreover, the grab does not fill up completely.

Consumption of Current during One Round of Operations with the Crane.

Concerning the current consumption, it should be noted that the intermittent working of a crane causes a useless consumption of current owing to resistance losses. This is further increased where the crane-driver, using direct current, does not take advantage of series wound motors for lifting smaller loads more rapidly than greater loads. The manner in which the transport equipment is handled may also play an important

part in the current consumption. In addition, the current consumption is determined to a great extent by the number of secondary movements, which can be reduced to a minimum by a judicious selection of the means of transport.

Current consumption for one round of operations of the crane taken as 0·6 of a unit:—

Current consumption per hour—$25 \times 0{\cdot}6 = 15{\cdot}0$ units.

Current consumption per ton of ore hoisted—$\frac{15{\cdot}0}{75{\cdot}000} = 0{\cdot}2$ of a unit.

Cost of Current.

Taking the cost of a unit as 0·5d.; the cost per ton $= 0{\cdot}2 \times 0{\cdot}5 = 0{\cdot}10$d.; and the cost of maintenance and repairs per ton of ore hoisted = 0·08d.

Workmen's Wages.

	s.	d.
2 crane-drivers at 7s. 6d. per day	15	0
4 labourers in ship at 4s. 6d. per day . .	18	0
2 labourers at bins at 4s. 6d. ,, . . .	9	0
	42	0

With a working day of 20 hours—the wages = 2·1s. per hour = 25·2d. = 0·336d. per ton per hour.

Cost of installing a bridge, complete = 64,000s.
Standing charges = 15 per cent. of initial cost = 9600s., or,
Assuming 7000 working hours in the year = 1·37s. per hour = 16·5d. = 0·22d. per ton per hour.

Table of costs per ton of ore transported from the ship to the bunkers (average weight), assuming 7000 working hours per annum and a quantity of 75 tons dealt with per hour—

Standing charges	0·22d.
Workmen's wages	0·34d.
Maintenance, &c.	0·08d.
Cost of current	0·10d.
	0·74d.

Assuming the ore yields $33\frac{1}{3}$ per cent., the cost is 2·22d. per ton of pig iron.

The reduction in the quantity dealt with per hour, which brings about a rise in the cost per ton for conveying, depends on various circumstances. The utilisation of the full capacity of the loading bridge is determined by the regular supply by the type of ship and the nature of the material in respect of size and hardness. A correctly dimensioned transporting receptacle is necessary for utilising the full carrying capacity of the grab.

With this type of loading bridge, it is possible in about four hours to discharge into the bins 10,600 cubic feet of ore stored on an area of 1550 square feet, the weight of the ore being 125 lbs. per cubic feet; the discharging being carried out by two bridges alongside of each other, each of 75 tons per hour capacity, the current consumption being 120 units for hoisting and travelling. The consumption of current for shifting the water-side end of the bridges a distance of about 35 feet does not amount to half a unit.

In a loading plant of this kind, the warping of the ship and shifting of the loading bridge are avoided, as previously stated, by having a slewing crane running on the bridge. In this case the draw-in jib of the bridge is done away with. The use of a slewing crane (which has been abolished in the large loading plants at the great lakes in the United States) may quite well be justified where different types of ore are smelted, and not similar kinds as in the United States. The slewing crane can unload from different hatches of the vessel, and pile the material at both sides of the loading bridge. Plate V. shows a loading plant of this kind.

For supplying the daily requirements of the blast-furnaces and distributing the stock according to types of ore, a series of bunkers is provided along the row of furnaces, an electrically-driven distributing wagon travelling over the bunkers. The distributing wagon receives the material from a hopper at the landing end of the bridge; the hopper can be loaded by the slewing crane.

The function of the distributing wagon is to deliver quickly to the bunkers attached to each blast-furnace the various sorts of ore, which may number as many as 30.

An efficiency of 70 tons per hour, using the maximum

trolley travel and radius of slewing, is attained by a bridge constructed according to the following specifications:—

	Feet.
Span of bridge	286
Travel of slewing crane	334
Radius of slewing crane	46
Height of lift	85
	Tons.
Carrying capacity of crane	5
Weight of grab	2·3
Capacity of grab	2·5
Direct current	440 volts.

The working speeds and motor outputs are as follows:—

	Feet per Second.	Horse-Power.
Travel of bridge	1·3	35
Travel of crane	8·2	2×25
Slewing of crane	1·0	7
Lift	2·62	70

While the slewing crane is feeding the hopper at the end of the bridge, the wagon is distributing the material into the bunkers near the blast-furnaces. The aim is, therefore, to move the heavy loads at low speeds and the light loads at high speeds. In this manner the current consumption when running light is appreciably reduced.

The conveyance of ore direct from the stock heap to the blast-furnaces would be too complicated, owing to the number of kinds of ore dealt with, and the storage of the whole stock in bunkers is expensive.

The height to the under side of the bridge is 38 feet, so that material can be piled to a height of 36 feet.

The material is drawn off from the bunkers into tipping wagons, and taken by the workmen to the inclined hoist. The capacity of the bunkers is sufficient for a two days' supply. Three blast-furnaces, each producing 180 tons of pig iron, have to be supplied, which works out at $3 \times 450 = 1350$ tons of ore to be conveyed.

A round of operations of the crane requires, on the average, 130 seconds, consisting, as it does, of collecting the material in the grab from the ship, hoisting the grab, travel and slewing

of crane, discharging grab over hopper, return journey and lowering to ship.

The current consumption for a round of operations is $0{\cdot}8$ unit $= 25 \times 0{\cdot}8 = 20{\cdot}0$ units per hour $=$ approximately $0{\cdot}3$ unit per ton of ore hoisted. Assuming that current costs 0·5d. per unit, the cost of current per ton of ore is $0{\cdot}3\text{d.} \times 0{\cdot}5\text{d.} = 0{\cdot}15\text{d.}$

Maintenance, repairs, spare parts, and lubrication = 0·04d. per ton of ore.

Wages (charging of the bunkers is only carried on for ten hours per day):—

1 crane driver	7s. 6d.
4 labourers in ship at 4s. 6d.	18s. 0d.
	25s. 6d.

The annual quantity of ore required is roughly 500,000 tons. In order to cope with irregularities of supply, three loading bridges, each of 700 tons daily capacity, are erected.

Summary of working expenses for one loading bridge having an annual capacity of 210,000 tons:—

	Shillings.
Initial cost	130,000
	Shillings per Year.
Standing charges (7·5+5 per cent.) .	16,250
Wages	9,310
Employers' insurance contributions, &c. (6 per cent. of wages)	560
Repairs, &c.	700
Cost of currrent	2,625
Total cost for conveying	29,445
	Shillings.
Total conveyance charges per ton of ore .	0·141
Total conveyance charges per ton of pig iron, assuming a yield of $33\frac{1}{3}$ per cent. from the ore	0·423

Where the distance between the place of unloading and the place of consumption renders it impossible to employ loading bridges (the limit for the construction of such bridges is about 600 feet = span + radius of slewing crane at both sides), transport is effected by means of aerial ropeways (telpher lines).

The Aerial Ropeway (Plate VI.).

Aerial ropeways are specially suitable in cases in which the site of the works does not permit of the installation of steam or electric railway owing to the cost of permanent way. Instances of this kind are hilly ground, waterways, and cross roads. The increased demand on the efficiency of the aerial ropeway has almost done away with the usual single rope type previously employed in England, America, and France. In this type the one rope was used both as the carrying and hauling rope, and the type can only be employed where the output is low and the distance covered short.

The German system of aerial ropeway for unlimited outputs and distances consists of a rope, serving as track, firmly stretched at the initial and end stations, and a movable endless traction rope kept permanently in motion by the driving motor. The disadvantage of a single ropeway is, in particular, the great wear of rope. All improvements of the double ropeway aim at reducing the wear of rope to a minimum, and, especially, at increasing the life of the carrying rope. For this reason the "patent locked" rope, with its smooth surface, has been introduced, and the trolleys are provided with a four-wheeled carriage, the four rollers being supported in pairs in compensated bearings. This method of supporting ensures that even where the trolley oscillates or runs off the straight, the pressure is distributed equally over all four wheels of the trolley. Trolleys so designed take switches and crossings and pass over rope couplings and intermediate suspenders without shock.

At the loading and unloading station, the aerial ropeway changes over into a suspended railway, on to which the trolleys are run to the filling and discharging places. The quantities transported are weighed here on automatic weighing machines, great importance being attached in blast-furnace work to the accuracy of the weighing.

The return carrying rope for the empty trolleys is often of the same diameter as the rope on which the loaded trolleys run. The life of the traction rope is dependent in particular on the course of the line. On a line having many curves

and differences of altitude, resulting in the rope bending in various directions, the life may be taken as not longer than six months. The durability of the rope is further affected by the time-intervals of the cars and the diameter of the guide rollers. The greater the time-intervals and the larger the diameter of roller, the longer the life of the rope.

The carrying ropes last from one to two years, according to the length of the line. It is subjected to most wear at the couplings; and thus the passage over the coupling is made as smooth as possible.

Both carrying and traction ropes require careful attention and sufficient lubrication.

The working expenses of an aerial ropeway are made up of (1) wages of staff required for working; (2) cost of power for driving the traction rope; (3) lubrication of the loading and unloading stations—mechanical parts, ropeways, and trolleys; (4) maintenance and repairs to plant.

The standing charges may be taken as 12 per cent. on the initial cost for depreciation, and 5 per cent. for interest.

Since in an aerial ropeway a number of rotating parts are employed, which, especially in transport work, require a great deal of attention (neglect of this point may cause an interruption to the working of the entire plant), a stock of spare mechanical parts must be kept, and included in the cost and depreciation. In a well-thought-out design, and by employing parts of a similar nature, it is possible to reduce somewhat the number and type of spare parts stocked. On the other hand, the item for maintenance and repairs can be credited with the old material and discarded portions of rope.

Regarding item (1) above, the staff required for driving comprises the engineman at the working station (generally the loading station), and labourers at the loading and unloading station, as well as those distributed along the line to inspect the transport. The number of the latter depends both on the length of the line and the rate of despatch of the trolleys; and finally, on the working efficiency of the entire plant, which may be arrived at after it has been in operation some time.

Calculation of Cost of Plant and Working Expenses of an Aerial Ropeway.

Daily output	1500 tons.
Length of line	6 miles.
Material transported	Medium-sized ore weighing 125 lbs. per cubic foot.
Load of a tub	1320 lbs.
Tare of the tub	990 lbs.
Capacity of tub	12·4 cubic feet.
Speed of haulage	6 feet per second.
Number of tubs to be conveyed	$\frac{168,000}{1,320}=125$ per hour.
Time interval between each tub	$\frac{3600}{125}=29$ seconds.
Distance between tubs	174 feet.
Number of loaded tubs on line	180
Number of tubs on line	360
Diameter of traction rope	$\frac{5}{8}$ inch.
Power transmitted by rope drive	120 horse-power.
Requisite current supply	$\frac{120}{0·8}=150$ horse-power.
Current consumption of motor	$150 \times 0·736=110$ kilowatts.
Period worked	350 days of 20 hours.

1. *Wages.*

2 engine-drivers at 7s. 6d.	180d.
6 loading labourers at 4s. 6d.	332d.
6 unloading labourers at 4s. 6d.	332d.
20 line attendants at 4s. 6d.	1080d.
Total wages per working day	1924d.
,, ,, ,, hour	96·2d.
,, ,, ,, ton	1·3d.

Not including the line attendants, the wages per ton of ore transported=0·56d.

2. *Cost of Current.*

	Units.
Current consumption: 20 hours at 110 kwts.	2200
Lighting of station and line	80
	2280

Cost per unit=0·5d.

Cost of current per working day: 2280 × 0·5	1140d.
,, ,, ,, hour	57d.
,, ,, ,, ton of ore	0·76d.

3. *Cost of Lubrication.*

	Shillings.
Loading (driving) station, per annum	500
Unloading station	350
Loading and unloading stations, per annum	850
Per mile per annum	450
For every 6 miles, per annum	2700
Per tub per annum	8
For 360 tubs, per annum	2880
Total annual cost for lubrication	6430
Total cost per working hour	$\frac{6430}{7000}$=0·92 sh.=11d.
Total cost per ton of ore	0·15d.

4. *Cost of Maintenance and Repairs.*

	Shillings.
Loading and unloading station, per annum	1000
Per mile per annum	1200
For 6 miles, per annum	7200
For the tubs	7000
Total per annum	15,200
,, ,, working hour	2·2 sh.=26·4d.

Cost per ton of ore=0·35d.

5. *Standing Charges.*

	Shillings.
Cost of installation—63,600 feet rope, $1\frac{3}{4}$ inch diameter; weight at 35 kilos per 10 feet=222,600 kg. for 63,600 feet; price of carrying rope at 10d. per kilo	185,000
64,000 feet traction rope, $\frac{5}{8}$ inch diameter; weight at 3 kg. per 10 feet=192,000 kg. for 64,000 feet; price of traction rope at 10d. per kilo	16,000
360 tubs, each 990 lbs., at 500 shillings	180,000
10 spare tubs	5,000
Driving station, mechanical parts, 6000 kg.	6,000
,, ,, iron construction, 10 tons	3,500
,, ,, electric equipment	4,000
,, ,, installation	300
Unloading station, mechanical parts	4,000
,, ,, ironwork	3,500
Supports for rope on line, 150, 18 feet high, 1·2 tons	54,000
Stays, 40 tons at 200 shillings	8,000
Foundations for stations and rope supports: 6·6 cubic yards for each support=150×5×15 shillings	11,250
66 cubic yards for the stations	750
Stretching weights, 40 cubic yards	450
	481,750

	Shillings.
Intermediate station, mechanical parts . .	800
,, ,, ironwork, 5 tons . .	1,750
,, ,, foundations and stretching weights . .	450
	3,000

	Shillings.
Total cost of installation	484,750

15 per cent. standing charges per annum .	72,712·5 shillings.
,, ,, ,, ,, working hour	10·9 = 130·8d.
Standing charges per ton of ore	1·75d.
Summary—	
(1) Wages	1·30d.
(2) Cost of current	0·76d.
(3) Cost of lubrication	0·15d.
(4) Cost of maintenance and repairs .	0·35d.
(5) Standing charges	1·75d.
Total charge per ton of ore conveyed, assuming flat ground and one intermediate station and an output of 75 tons per hour .	4·31d.

Blast-furnace Charging.

The requirements of hoisting appliances for charging blast-furnaces may be said to be: safety of working, efficiency, accuracy of control of the driving mechanism, economy, simplicity of construction and manipulation, saving of space and labour.

As regards the blast-furnace itself, the points requiring attention in the selection of hoisting machinery are: maximum protection of the coke, prevention of gas escaping during charging, uniform distribution of material in the furnace.

The transporting arrangements should be designed so as to prevent falling of the coke. The coke should be moved with a sliding motion only. Hoppers with slides for closing cannot be said to be satisfactory, since the material is considerably reduced in size thereby. In order that the coke may be transhipped as little as possible, the simplest plan is to bring the blast-furnace charging receptacle direct to the coke-oven plant, where the coke can be loaded direct from the quenching bed into the particular vessel; or, where coke-comes by rail, it can be shovelled from the trucks into the transporting

vessel. Unloading coke by hand is the best way of preserving it, and this is the method generally adopted.

A blast-furnace with a daily pig iron production of 200 tons also consumes 200 tons of coke per day. Taking coke at 18s. 6d. per ton, and assuming 1·7 per cent. abrasion for the two transhipments, the loss of coke $= 3 \cdot 4 \times$ 18s. 6d. $=$ 63s.; while with one transhipment (0·89 per cent. abrasion) we get $1 \cdot 78 \times$ 18s. 6d. $=$ 34s. If, therefore, one transhipment is saved this represents a saving of 29s. per day per furnace—a saving per annum of £530.

The precautions to be observed for preserving the coke extend to the arrangement of the furnace top. The older arrangement of charging with tipping buckets, where the coke often fell from a height of 46 feet, cannot be considered as economical in spite of the saving in wages (only one mechanic is necessary for attending to the hauling engine). On the other hand, charging by means of hopper buckets may be considered as the best solution, being even preferable to the arrangement employing skips hanging on overhead runways. In the case of the hopper bucket, the material is only transhipped once, and it slides rather than falls into the furnace.

With suspended skips the coke falls from the skip first on to the bell and then into the furnace, the height of fall being about 30 feet.

Charging by means of hopper buckets, however, satisfies all other conditions of economy in blast-furnace charging.

During the emptying of the bucket, the bucket itself forms the seal of the furnace top, thus preventing the escape of gas. No labour is required actually on the furnace top.

The charging proceeds quite automatically, and is not dependent on the workmen who have, as in the case of the electric suspended railway, to see to the mixing of the charge. This latter operation, when undertaken on the furnace top, cannot be continually supervised by the leading hand of the blast-furnace.

With an electric telpher line it is necessary to have, as a rule, four workmen on the furnace top for tipping and shunting the tubs, and for attending to the bell windlass. With a

number of furnaces alongside each other, this number of men can attend to two furnaces.

The steady operation of the hopper bucket transporting system, as compared with the bumping of the cars and the unsteady running at the points of the telpher line, often effects saving in repairs. Owing to the tubs having often to be changed, the telpher line requires a large stock of spare parts and, owing to the large number of block switches, permanent and expert supervision of the entire line—a matter of great expense. The failure of a single switch may bring the whole line to a standstill.

The depreciation charges in the case of the various working parts vary according to the importance of the parts and the demands placed upon them. The parts most exposed to the heat of the furnace require renewal more often. The most expensive item is the long and thick ropes for the inclined hoists.

Lilge gives the following rates of depreciation:—

	Per Cent.
Concrete work, foundations	3·0
Rails, &c.	3·0
Anchoring	3·0
Ironwork	5·0
Material of skips	8·0
Material of transport cars	10·0
Machine parts	10·0
Electrical machine parts	12·5
Hand and telpher tubs	12·5
Hoisting chains and ropes	100·0
Suspension ropes	25·0–250·0

Charging by Means of Hopper Buckets.

For transporting the hopper buckets to the furnace top, use is made of inclined hoists from which the bucket is suspended. The inclined hoist consists of parallel lattice-work girders with upper and lower members formed as tracks. The form of hoist most used in Germany is that based on the Hunt type usual in America; this type is being gradually introduced in England, where it has a tendency to displace the steam hoists. The German types are those constructed by "Stähler-Benrath" and J. Pohlig, A.G. In the Stähler-Benrath system a lifting

trolley, operated by a haulage rope from the power-house, runs on the lower track of the frame, which trolley is counterbalanced by a weight travelling on the upper runway or track and connected with the trolley by a steel rope. The hoist frame is supported at the top by means of roller bearings on the furnace shaft, or by special supports, and is anchored at the bottom in a solid foundation.

In J. Pohlig's type, a motor trolley moves up and down on the upper member of the frame by means of a spur gearing and a rack laid along the runway. The motor trolley obtains its current from a conductor laid along the runway, and draws along with it another trolley (from which the skip is suspended) running on the lower runway, and connected to the motor trolley by a rope. The motor trolley or traveller is controlled from a cabin on the hoist frame or on the top of the furnace.

In the Stähler-Benrath system (Fig. 10), the lower runway on reaching the furnace top is carried to the centre of the furnace, the check rail being deflected outwards. On the arrival of the trolley the front wheels run on the lower track, together with the bucket, to the centre of the furnace, while the trailing wheels bear on the check rail. This secures that the buckets are deposited on the top without shock or oscillation. In this case the seal of the furnace consists of a simple bell opening automatically when the bucket is placed on the top. Before the bell opens the cover has descended automatically on to the bucket, so that no escape of furnace gases takes place.

In the Pohlig system (Fig. 11) the lower runway ends in a fork projecting over the centre of the furnace, and the bucket is lowered by the front wheels of the bucket trolley running out on to a rocking lever forming the upper part of the fork, the bucket being lowered on to the furnace top when this lever descends. The rocker also serves for partially equalising the surplus weight of the load.

The charging buckets themselves have their lower part made conical so as to fit into the top hopper; while in the inside they have a conical bottom connected by a rod with the cover and the hoisting rope of the hoist. The cover automatically drops on to the edges of the bucket, without shock, when the latter is inserted on the top hopper, this operation being

carried out in conjunction with the lowering motion of the trolley. When the bucket is emptied and the furnace closed by the bell, the lid of the bucket is lifted, so that any gas present in the bucket may escape during the downward journey.

The drive of the Stähler-Benrath hoist consists generally of

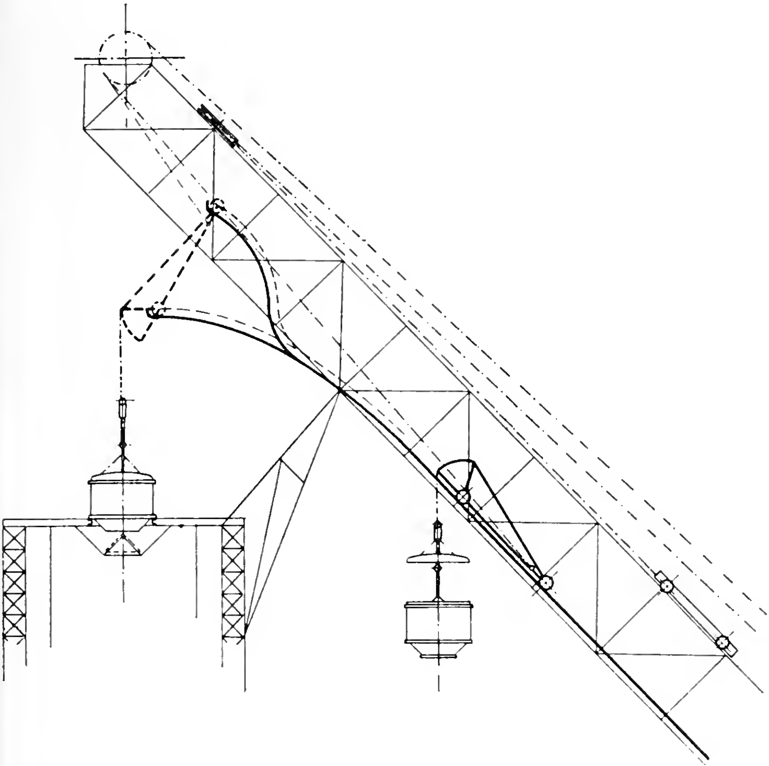


FIG. 10.—Stähler-Benrath Blast-furnace Hoist.

two electric motors, one of which drives the rope drum by intermediate spur gearing, while the other serves as a dynamo for braking purposes. The lifting motor has a safety control with arrangement for automatically retarding and switching off at the upper and lower limits of lift. Emergency brakes can be applied either automatically by a depth gauge (if the regular stopping places have been passed), or by a hand lever

when the trolley is at any position. The current is switched off by a brake drum operated by the spiral nut of the depth gauge. The controller for the lifting mechanism need only be moved at the beginning and end of the lifting motion,

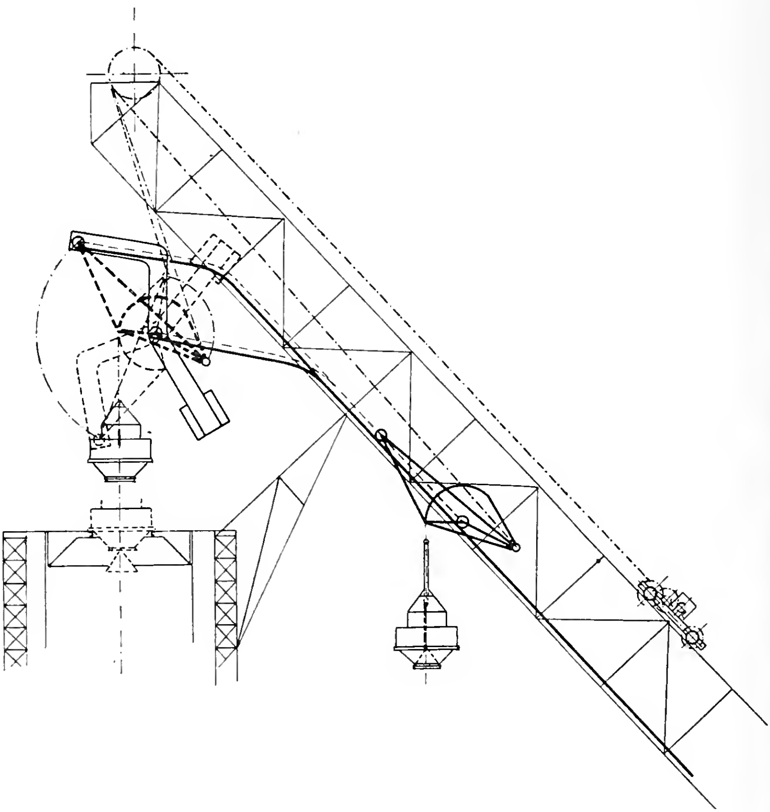


FIG. 11.—Inclined Pohlig Blast-furnace Hoist.

while the trolley is in motion no movement of the controller is necessary.

Instead of the back current motor drive and safety control, the Leonard method is also employed.

The working efficiency of the Pohlig hoist depends mainly upon the action of the electrically operated brakes at the extreme positions of the trolley and when the bucket is

lowered on to the furnace top. These brakes are worked automatically in conjunction with a depth indicator. Emergency brakes, connected with the depth gauge and actuated by centrifugal switches, prevent too high a speed of the trolley. The Leonard method provides in this case a simple and accurate means of controlling the speed, thus rendering electric brakes superfluous.

The use of the Leonard arrangement in connection with inclined hoists is more expensive than the safety control with ordinary arrangement of motors; the former is, however, economical in the case under discussion, as the working periods are very great compared with the time the hoist is not working, and the expenditure of power by the controlling set (controlling dynamo and its driving motor) is not wasted on useless work.

The operation of the attaching and detaching of the hopper bucket from the trolley can be easily and rapidly carried out by one workman. In more recent types of Stähler-Benrath hoists, as constructed by the Deutsche Maschinenfabrik A.G., of Duisburg, the attaching and detaching are effected by means of a suspension column slipped into the suspension bar of the bucket, with the aid also of the raising and lowering motion of the platform for the transporting bogies (Stahlwerk Thyssen, Hagendingen).

The transport bogies for the travelling buckets are simple electrically-driven platform bogies, with self-contained controlling gear, and sometimes equipped with a slewing crane. In the latter case, the buckets are taken on by the crane and lowered into a 7 feet deep pit, filled there by means of hand-tipping tubs (generally used only with coke) and hoisted up again by the slewing crane, and carried back to the hoist. The charging platform for the bogies is an electrically-driven turntable which rotates during the operation of filling from one bunker door to another. This secures uniform filling of the bucket, and at the same time a good mixing of the charge.

Before being received by the hoist the charge is weighed on the transporting bogie, the platform of which is connected with an automatic weighing machine.

The taking up of the buckets from different directions

necessitates carrying the frame of the inclined hoist horizontally (above ground) to beneath the bunkers or coke beds.

Plant "A." (See Plate VII.)

It is desired to supply four furnaces, each producing 400 tons of pig iron per day. With a 40 per cent. extraction (charge, 25 per cent. Swedish ore, 40 per cent. minette, 35 per cent. slags and fluxes), this represents a quantity of 4000 tons of ore and 1600 tons of coke to be transported per day. The general arrangement is shown in Plate VII. The ore is delivered by rail.

The buckets are each of 8·5 cubic metres capacity.

A charge represents three buckets of 6·67 tons ore = 20 tons.

A charge represents two buckets of 4 tons coke = 8 tons.

The speed of hoist is 72 metres per minute.

Calculation of Costs of Installation and Working.

The charges for ore transport commence with the discharging from the railway wagons (one-half being standard goods wagons, and one-half automatic unloaders) over bunkers and stock yard; and for the coke transport they commence with the despatch of the buckets from the transport wagons on the cranes.

I. *Standing Charges* (*Depreciation and Interest*, 5 *per cent.*).

(1) *Ore Bunkers:*

	Shillings.
22 bunkers, each holding 2100 cubic metres, complete with helmet closing traps, elevated railway lines, steps, lighting: initial cost	974,508·40

	Shillings.
Depreciation	35,628·93
Interest	48,725·42
Standing charges per annum	84,354·35

(2) *Elevated Railway over Stock Ground: Piers, Elevated Railway with Lines, Slag Cement:*

	Shillings.
Initial cost	133,314

	Shillings.
Depreciation	5,409·18
Interest	6,665·70
Annual standing charges	12,074·88

(3) *Suspended Railway Plant:*

Initial cost—

	Shillings.
Under bunkers	47,286
At the stock yard	57,306
At the scrap storage	21,037
160 suspension tubs	52,000
48 unloading hoppers with bottom shoots . .	25,680
24 double flap door	12,000
Cost of installation	215,309

	Shillings.
Depreciation	16,126·44
Interest	10,765·49
Annual standing charges	26,891·93

(4) *Travelling Platforms:*

	Shillings.
8 travelling platforms with weighing devices (cost of each complete about 11,000 shillings), crane track, wiring, lighting: cost of installation	107,766

	Shillings.
Depreciation	10,021·80
Interest	5,388·30
Annual standing charges	15,410·10

(5) *Operation of Transporting Bogies:*

	Shillings.
4 50-metre channels with rails and four electrically-driven sludge pumps	106,800
4 bogies with double drive, 8 buckets at 13·50 shillings each, wiring and lighting . .	86,920
Cost of installation	193,720

Depreciation	11,803
Interest	9,686
Annual standing charges	21,489

(6) *Drive for Coke-Skips:*

	Shillings.
4 cranes, 10 tons × 12 metres, crane track, foundations, wiring, lighting—	
Cost of installation	143,806

Depreciation	11,939·70
Interest	7,190·30
Annual standing charges	19,130

(7) *Working of Inclined Hoists:*

4 inclined hoists (frame, rope, drums, supports on blast-furnace shaft, anchoring, wiring)	Shillings.
Cost of installation	490,980

	Shillings.
Depreciation	42,107
Interest	24,549
Annual standing charges	66,656

	Shillings.
Of this total, for ore transport: 60 per cent. =	39,993·60
,, for coke transport: 40 per cent. =	26,662·40

II. *Wages.*

Number of workmen and foremen required during 24 hours, and their wages per shift.

(1) *For Discharging Ore Wagons into Bins and on to Storage Ground:*

40 workmen at 4·20 shillings.
1 foreman at 5·20 ,,
1 labourer for breaking the Swedish ore at 3·50 shillings.

Annual wages—83,658 shillings.

(2) *For Withdrawing Ore from Bunkers:*

(32 workmen at 4·40 shillings): loading Swedish ore (24 at 4·40 shillings); loading scrap (8 at 4 shillings).

Weighers (8 at 4·90 shillings); foremen (4 at 5·70 shillings); travelling-platform drivers (16 at 4·30 shillings); transporting bogies' drivers (8 at 4·70 shillings); coke-skip crane-drivers (8 at 4·50 shillings).

Annual wages—194,180 shillings.

Of this total, for ore transport—168,367·20 shillings.
,, for coke transport—25,812·80 ,,

(3) *Inclined Hoist Drivers:* (8 at 4·50 shillings).

Annual wages—22,995 shillings.

(4) For wiremen (4 at 4·80 shillings).
,, electricians (2 at 5·60 shillings).
,, fitters (leading hands) (2 at 5·60 shillings).
,, fitters (4 at 4·70 shillings).
,, greaser (1 at 4·40 shillings).
,, motor men (2 at 4·50 shillings).

The wages under this heading (4) have already been included in the wages given under (2) and (3).

Total Annual Wages—300,833 shillings.

	Shillings.
Contributions in respect of Employers' Liability and Sickness Insurance=6 per cent. of the wages	18,700

III. *Repairs, Maintenance, and Renewals.*

	Shillings.		Shillings.
(1) *Ore Bunkers, Elevated Railway:*	1,500	per annum.	
Suspended railway, doors	1,500	,,	
Travelling platforms	6,240	,,	
Coke-skip cranes			4,320
Bogies, for ore buckets	5,112	for coke	3,408
Inclined hoists, for ore	13,200	,,	8,800
	27,552		16,528
Annual charges		44,080	

IV. *Lubricants and Cleaning Material.*

(Oils, bearing grease, rope grease):

	Shillings.		Shillings.
Suspended railway . .	120	per annum.	
Travelling platforms . .	840	,,	
Coke-skip cranes			640
Bogies for ore buckets . .	432	for coke	288
Inclined hoists	1,728	,, .	1,152
	3,120		2,080
Annual charges		5,200 sh.	

V. *Current Consumption.*

Cost . . . . . 0·03 shillings per unit.

(1) *Lighting of Ore Bunkers and of Store:*
240 units per 24 hours=2,628 shillings per annum.

(2) *Bogies*—Power Consumption:
Per journey for ore 0·298 unit } as measured by meter.
,, ,, coke 0·223 ,, }
For one furnace charge:
3 journeys for ore =0·894 unit.
2 ,, ,, coke=0·446 ,,
Shillings.
Cost for ore transport 1957·86 per annum.
Cost for coke ,, 976·74 ,,

(3) *Power Consumption for Travelling Platforms:*
From meter measurements, 0·704 unit per charge.
Annual charges, 1541 shillings (ore).

(4) *Power Consumption for Coke-bucket Cranes:*
From meter measurements, 1·896 units per charge.
Annual charges, 4152 shillings (coke).

(5) *Lighting under Ore Bunkers:*
80 units for 24 hours=876 shillings per annum.

(6) *Four Inclined Hoists:*

3-phase motors and D.C. brakes—

1 ore transport = 2·51517 units } as measured by meter.
1 coke ,, = 2·13685 ,, }

Lighting = 0·354 unit.

For ore transport, 1551·58 units in 24 hours = 16,989 shillings per annum.

For coke transport, 883·06 units in 24 hours = 9669 shillings per annum.

Summary of Initial Costs, also of Transport Charges per Annum.

	Shillings.
Initial cost	2,259,404·20
1. Standing charges	246,006·26
2. Wages	300,833·00
Employers' contributions	18,700·00
3. Repairs, &c.	44,080·00
4. Lubrication	5,200·00
5. Lighting, power, &c.	38,791·85
Transport charges	653,611·11

Transport Charges per 1 Ton of Pig Iron, with a Daily Production of $4 \times 400 = 1600$ *Tons = an Annual Production of* 584,000 *Tons.* (*See Diagram VIII.*)

	Shillings.
1. Standing charges	0·422
2. Wages	0·515
Employers' contributions	0·033
3. Repairs, &c.	0·075
4. Lubrication	0·009
5. Power, lighting, &c.	0·065
	1·119

Plant "B" in accordance with Plate VIII.

Output as in Plant "A." Details of the plan are shown in Plate VIII.

Sizes of buckets, &c., as in Plant "A." The working speeds of the wagons are:

Hoisting	18 metres per minute.
Slewing	Once per minute.
Travelling	120 metres per minute.

Summary of Initial Costs, also of Transport Charges per Annum for Plant "B."

	Shillings.
Initial cost	4,638,734
1. Standing charges	542,604
2. Wages	173,537
Employers' contributions	10,412
3. Repairs	52,350
4. Lubrication	6,610
5. Current consumption	36,302
Transport	821,815

Transport Charges per Ton, assuming an Annual Pig Iron Production of 584,000 *Tons. (See Diagram VIII.)*

	Shillings.
1. Standing charges	0·929
2. Wages	0·297
Employers' contributions	0·018
3. Repairs, &c.	0·089
4. Lubrication	0·013
5. Current	0·062
	1·408

Plant "C" in Accordance with Plate IX.

Output, &c., as in Plant "A."

Plant "B," the rails of the inclined hoist extension of which intersect the lines on which the ore feed-cars run, has been considerably improved upon in that the stocks in the ore bunkers are arranged so as to supply two furnaces situated between them, and the bogies bringing up the ore buckets (which, as in the case of Plant "B," run under the bunkers) have no need to cross the tracks of the inclined hoists of the two inside furnaces.

Since the ore bunkers (of sheet iron) only hold 40,000 tons with a capacity of 20,000 cubic metres, the remainder of the ores, amounting to 75,000 tons, are piled in the stockyard adjoining the bunkers. These ores are dealt with by two loading platforms of 20 tons carrying capacity and 75 metres span, being loaded from the stock pile into the bunkers by automatic grabs or buckets. The use of buckets is preferable where the material is not sufficiently piled up to allow of the grab (about 3 cubic metres capacity in the present case) being entirely filled. The material is shovelled into the buckets by workmen, and these are emptied into the bunkers by the operator from his cabin on the crane. Each loading platform deals with about 100 tons per hour at the following working speeds:

Hoisting	40	metres	per minute.
Travelling of trolley	150	,,	,,
Travelling of crane	10	,,	,,

In this plant a charge consists of two buckets of ore (2 × 10 tons) and two buckets of coke (2 × 4 tons), and in

one bucket of ore (10 tons) and one bucket of coke (4 tons) respectively.

The ways and means of transport for ore and coke are the same as in Plant "B."

Summary of Transport Charges per Annum.

		Shillings.
	Cost of installation of Plant "C"	3,435,712
1.	Standing charges	431,351
2.	Wages	186,385
	Employers' contributions	11,400
3.	Repairs, &c.	46,030
4.	Lubrication	5,402
5.	Current	41,739
	Transport charges	722,307

Transport Charges per Ton of Pig Iron, assuming an Annual Production of 584,000 *Tons.* (*See Diagram VIII.*)

		Shillings.
1.	Standing charges	0·738
2.	Wages	0·319
	Employers' contributions	0·019
3.	Repairs	0·079
4.	Lubrication	0·009
5.	Current	0·072
		1·236

Charging by Electric Telpher Line.

For charging the furnaces by an electric telpher line, use is generally made of a combination of this with the telpher ropeway. Since the frictional grip of the carriage is not great enough to enable the former to negotiate a gradient of more than 5 per cent., only the horizontal transport lines of the plant are arranged as electric telpher lines, having fixed rails and self-contained motor drive; while for overcoming the incline from the ground level to the charging platform the telpher ropeway system is employed, comprising a fixed rope or a fixed rail as the track and an endless haulage rope as the drive. In this case the electric line trolleys are fitted with devices for gripping the rope. The use of the haulage rope drive admits of maximum gradients of the inclined track,

thus considerably reducing the space required. The tubs are automatically clipped on to the haulage rope on passing from the horizontal track to the ropeway track; and also release themselves on the charging platforms and continue their journey, partly under power and partly by hand, on to the suspended track carried around the charging hopper on the top of the furnace.

The electric telpher line consists of a fixed line of rail, on which electrically-driven trolleys run by friction. From these trolleys is suspended a hopper bucket, generally a tipping one. Each trolley has one or two motors driving one or both wheels by means of spur gearing. In all cases direct current of 110 or 220 volts is employed. The motors of the electric telpher line trolleys are generally not more than 1 horse-power, and are provided with short-circuiting armature (compound wound). The trolleys have electro-magnetic brakes acting on the wheels or on the running rail. The possibility of laying the track of the electric telpher line in curves and of using switches increases the field of application of this system. By correctly arranging for the distance apart of the carriages, the efficiency of an electric telpher line plant may be considerably increased in case of need.

In order to save manual labour in the working of the telpher line, and to secure automatic and continuous working so that the trolleys can traverse any sections without supervision and without the danger of colliding, block switches are fitted along the track and secure the automatic stopping and restarting of the trolleys. With this end in view, the current conductor along the track is interrupted at certain intervals, thus insulating the individual sections of track from one another. The switching is effected automatically by the individual trolleys during the journey, the circuit being interrupted in the section just traversed until the wagon has reached the next section. In addition, however, hand switches are available, by means of which the trolleys may also be stopped and restarted.

Plant "D" in Accordance with Plate X.

Output as in Plant "A."

Ore Transport.—The conveying plant serving for the transport of ore only consists of a telpher rope railway *a* Bleichert's system, the tubs of which are filled from the ore bunkers *b* of ferro-concrete, with Züblin trap-doors, situated in front of the blast-furnaces. The bunkers are in six rows of twenty-five compartments each, parallel to the blast-furnaces. A telpher line runs under each row. In addition, a track for empty tubs and a track *c* for the telpher line tubs (which are loaded with scrap direct from the wagon) run along on the two extreme sides of the bunker plant. Behind the bunkers, at the base of the inclined track (in the form of a ropeway) to the charging platform, is a collecting place *d*, with a number of telpher lines corresponding to the number of furnaces to be supplied.

The tubs, coming empty from the furnace top and bearing numbers corresponding to the furnaces, travel under the ore bunkers, are filled and weighed just before the collecting place is reached.

The weighing device consists of a loose piece in the overhead rail of the length of the wheel base of the trolley or car, this loose piece being coupled with the weighing machine proper.

The further despatch of the tub from the collecting place to the charging platform is (for all furnaces and all tubs) attended to by one man situated in a switch cabin at the base of the inclined track. He receives a signal from the top of each furnace as to the kind and quantity of ore and lime required. By operating a pull switch, the man sends the required tubs to the furnace top.

On arriving at the charging platform, the tubs pass from the traction rope on to the suspended railway track by means of a sliding contact arrangement, and pass to the track pertaining to the individual furnaces. The tubs are then pushed by workmen to the charging hoppers, where they are tipped.

Assuming a working speed of the suspended railway of 1 metre per second, and a car capacity of 0·8 cubic metre

$=1250$ kilos of ore, the output per hour of the plant is 200 tons of ore. The 4000 tons of ore to be conveyed within twenty hours, therefore, necessitate 320 charges of ten tubs each. The interval between the tubs is in this case about 22·5 metres.

Coke Transport.—The coke is transported on the inclined track *e* from the ground level to the charging platform by means of suspended rail track with haulage rope drive on a special conveyor track. The double track inclined section, arranged as a haulage ropeway, takes up the tubs from a ropeway coming from the coke-ovens. The portion of the railway on the charging platform up to the stopping place of the tubs consists also of suspended track rail and haulage rope. From the stopping place the tubs are, as in the case of ore transport, conveyed further on by hand.

In order to increase the safety of the plant, the section over the inclined track and on the charging platform has a double drive. Spare haulage ropes are also provided, and lie alongside the working rope; they can be put into service if the latter is damaged in any way.

With a working speed on the inclined tracks and at the top of 90 metres per minute, using trolleys of 1·32 cubic metre capacity $=625$ kilos coke, the output per hour is 80,000 kilos. The 1600 tons coke to be conveyed in twenty hours necessitate, therefore, 320 charges of eight trolleys each. The interval between the trolleys is, in this case, about 42 metres.

The telpher line or suspended railway is carried around the whole of the furnace top, so that the material can be tipped at any position into the charging hopper, thus insuring uniform distribution. In this case the charging hopper does not rotate as happens when the material is carried only to one side where inclined hoists with tipping buckets are employed. The bell is operated from a cabin on the charging platform by means of an electrically-driven winch.

Summary of Annual Transport Charges.

	Shillings.
Cost of installation for Plant "D" .	3,681,340

I.	Standing charges	417,035
II.	Wages	188,685
	Employers' contributions	11,550
III.	Repairs, &c.	32,750
IV.	Lubrication	5,542
V.	Current	33,536
	Transport charges	689,097

Transport Charges per Ton of Pig Iron Assuming an Annual Production of 584,000 *Tons for Plant "D."* (*Diagram VIII.*)

		Shillings.
I.	Standing charges	0·714
II.	Wages	0·323
	Employers' contributions	0·020
III.	Repairs, &c.	0·056
IV.	Lubrication	0·010
V.	Current	0·057
		1·180

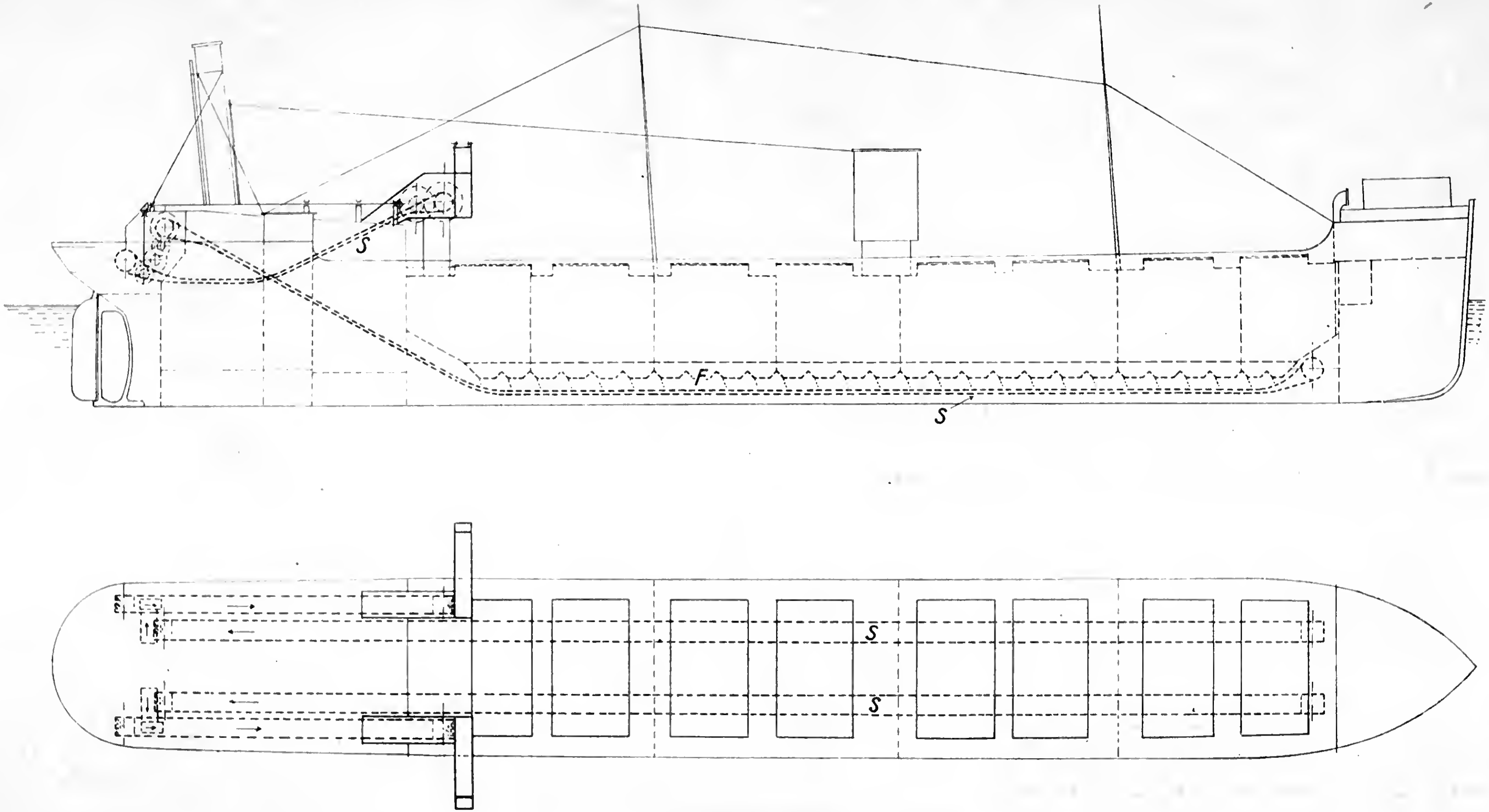
Comparison of Plants Described.

Table VIII. and Diagram VIII. contain in parallel columns the individual transport charges—(I.) Standing Charges; (II.) Wages and Employers' Contributions; (III.) Repairs, &c.; (IV.) Lubrication; and (V.) Cost of Current.

The highest standing charges are for Plant "B," and are caused by the inclined hoist frames being carried behind the bunkers; the charges on this account are twice as great as those for the transport from the store or from the bunkers to the furnace top in Plant "A," with the suspended railway working under the bunkers.

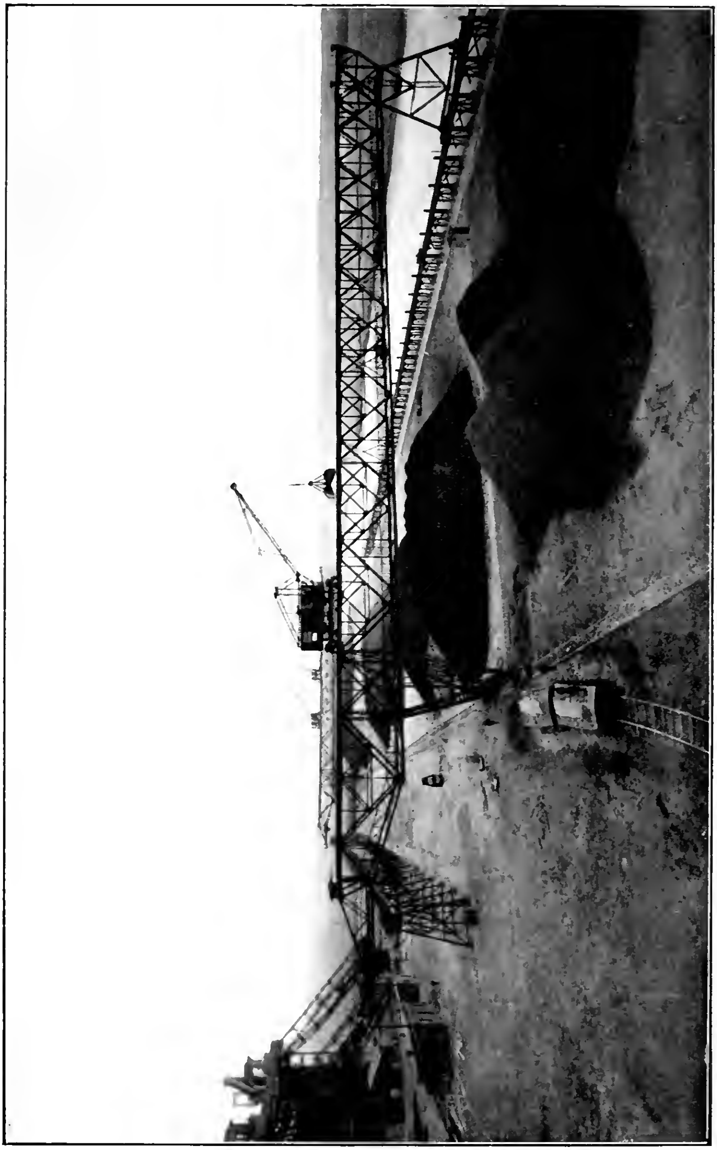
These higher initial charges are not compensated by the reduction in wages, which are lowest in this case of all the plants under consideration. In the case of the working with inclined hoists, although there is a saving in staff, the costs of installation for the mechanical equipments are too high, though, of course, the maximum safety of working is effected. If we take the product of number of workmen and standing charges per ton of pig iron as follows:

Plant "A"	188 × 0·422 = 79·3
,, "B"	106 × 0·929 = 98·5
,, "C"	110 × 0·739 = 81·3
,, "D"	110 × 0·714 = 78·5

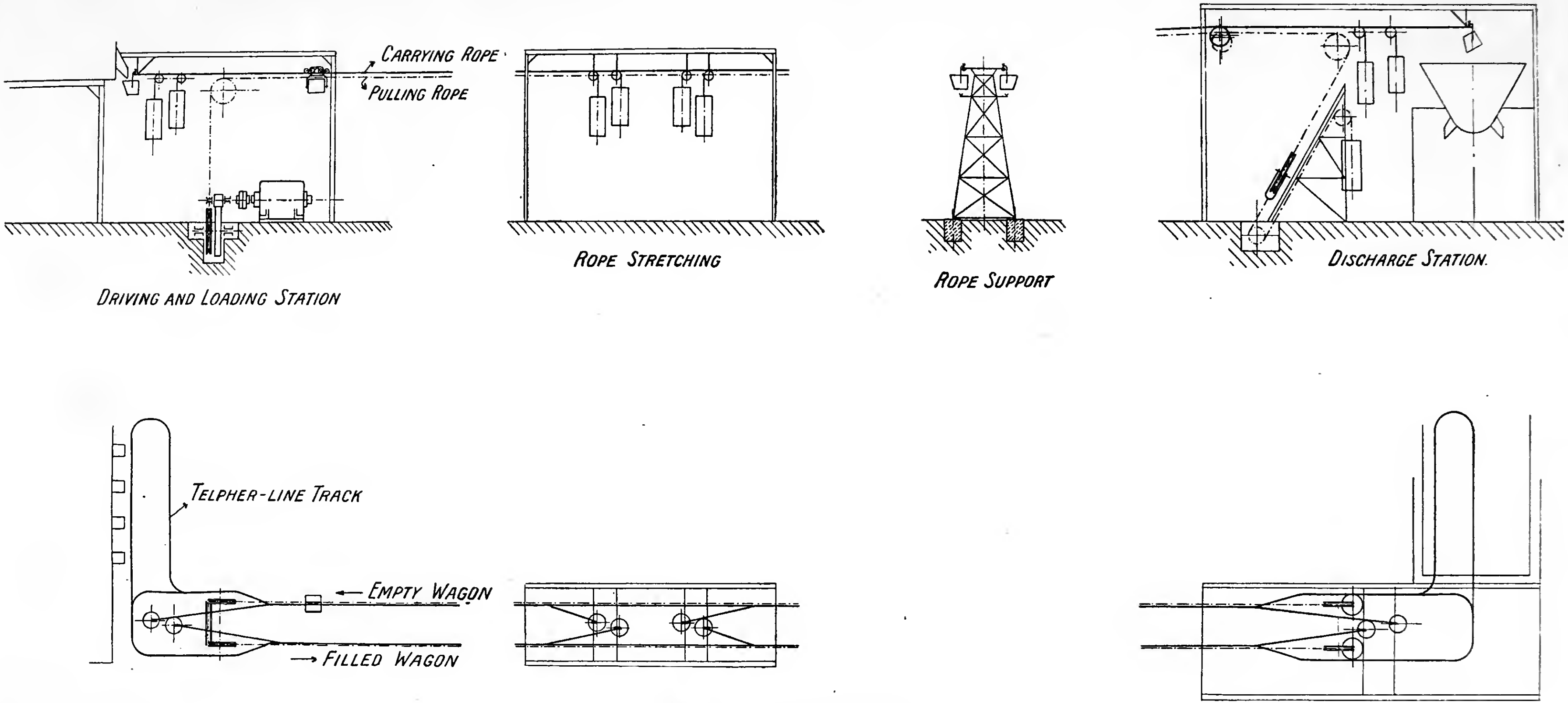


SELF-DISCHARGING COALING VESSEL. BELT CONVEYOR.

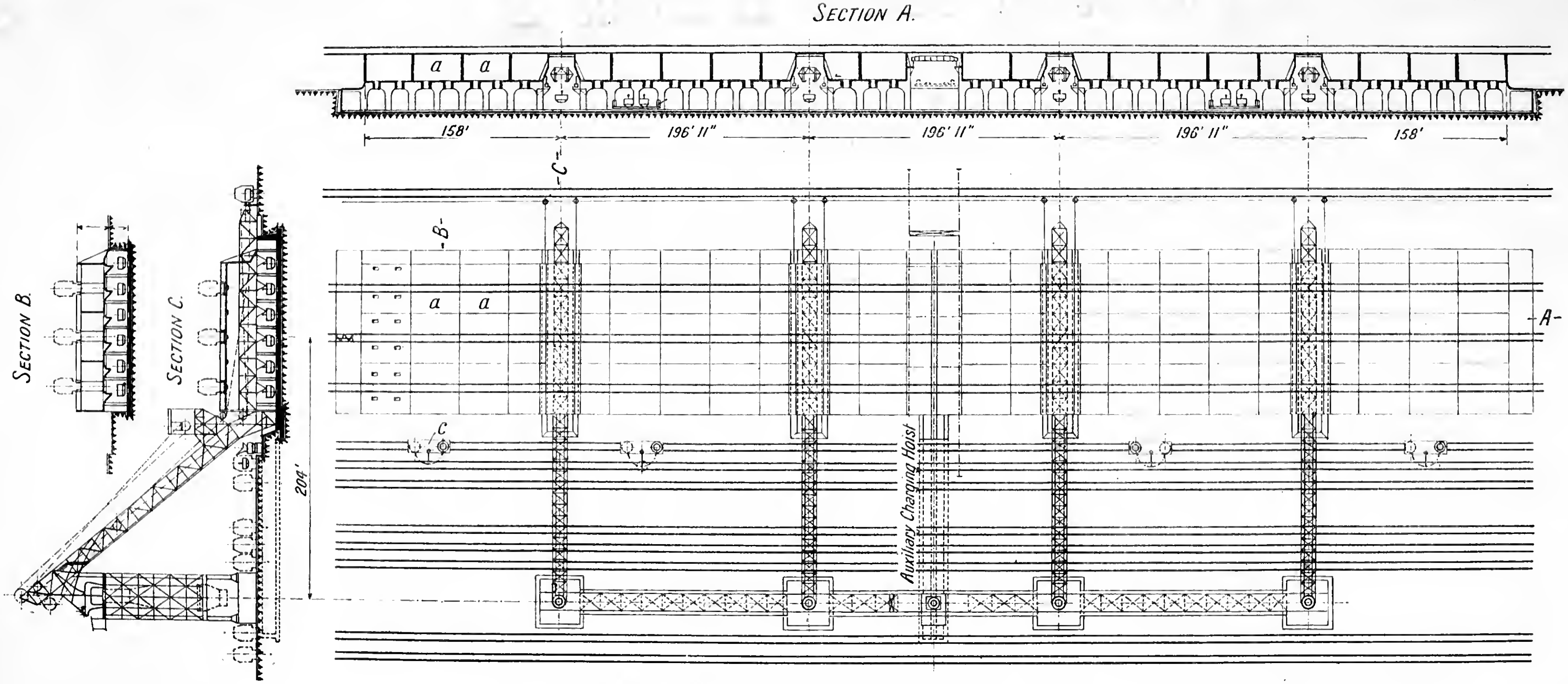
PLATE V



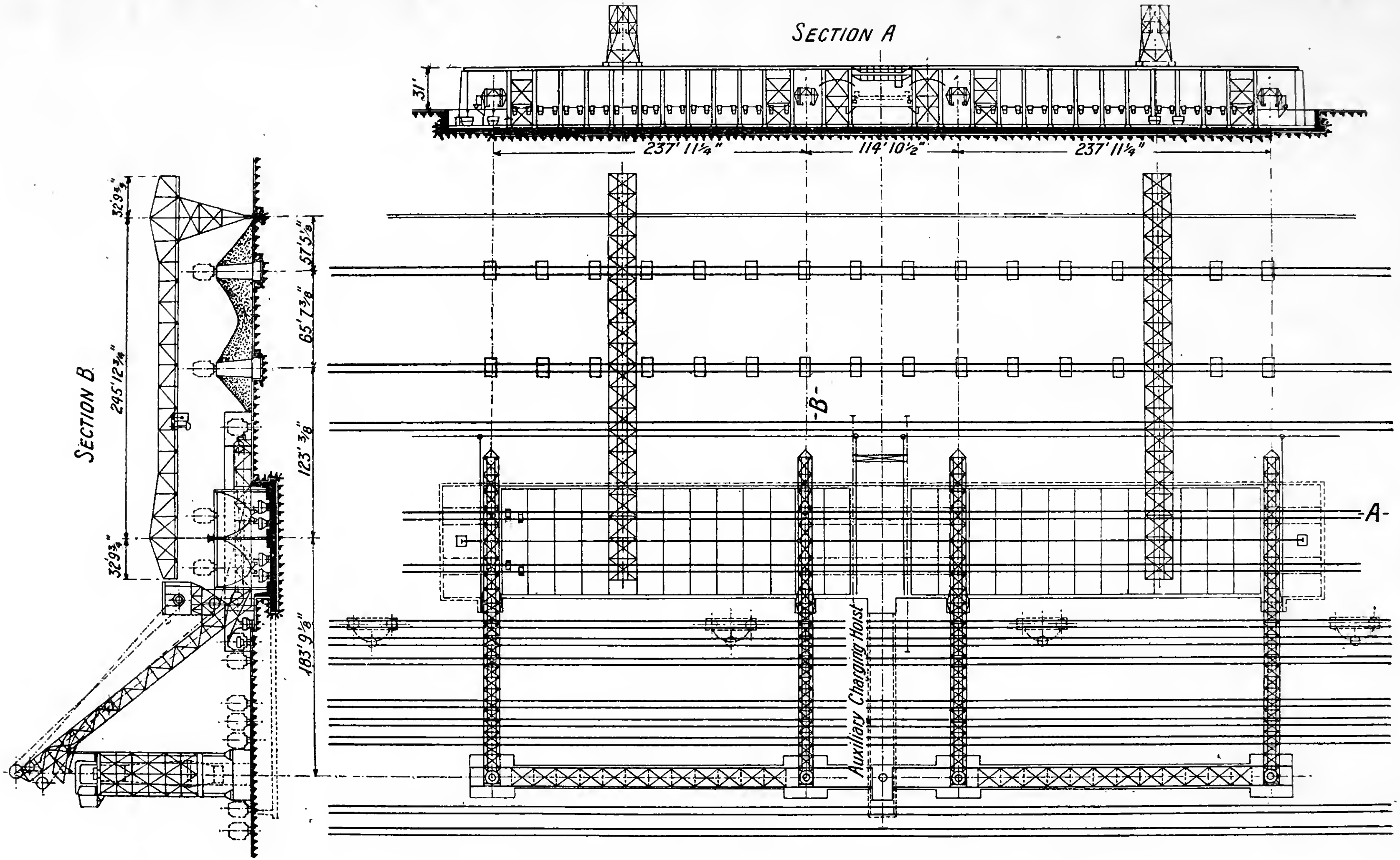
Loading Plant.



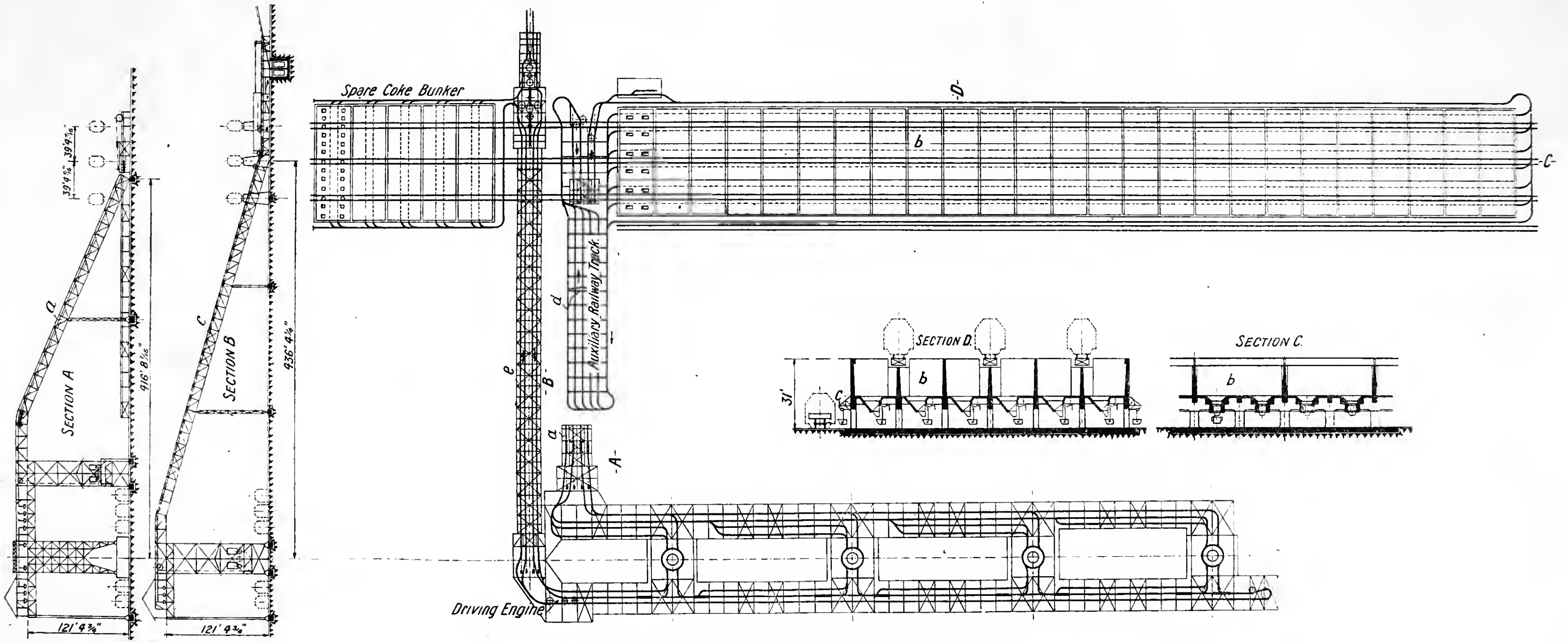
SCHEME OF AN AERIAL ROPEWAY.



SCHEME B.—BLAST-FURNACE CHARGING PLANT.



SCHEME C.—BLAST-FURNACE CHARGING PLANT.



SCHEME D.—BLAST-FURNACE CHARGING PLANT.

TABLE VIII.—*Detailed Cost of Transport in Shillings for the Installations A, B, C, and D per Ton of Pig Iron with a Daily Production of* 1600 *Tons in Four Blast-Furnaces.* (*See Diagram VIII.*)

	Installation Type.			
	A.	B.	C.	D.
Cost of installation	3·865	7·980	5·880	6·310
I. Standing charges	0·422	0·929	0·739	0·714
II. { Wages	0·515	0·297	0·319	0·321
II. { Employers' contributions	0·033	0·018	0·019	0·020
III. Repairs	0·075	0·089	0·079	0·056
IV. Lubrication	0·009	0·013	0·009	0·009
V. Current	0·065	0·062	0·072	0·057
Total transport costs per ton of pig iron	1·119	1·408	1·236	1·177

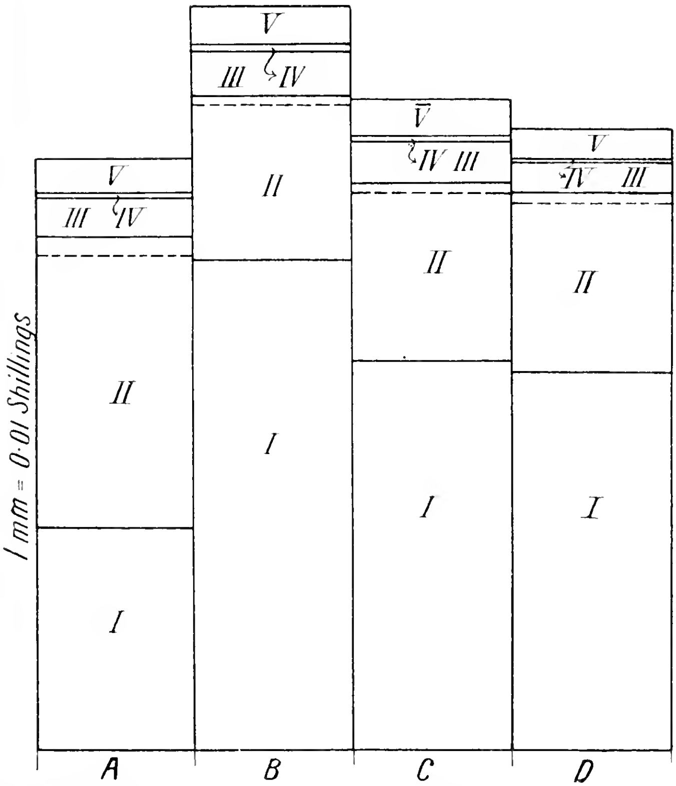


DIAGRAM VIII.—Comparative Costs of Installing Plants A, B, C, and D.

the result works out most favourably for the electric telpher Plant " D "; while if the product of wages and standing charges be taken:

Plant "A"	188×0·515=96·8
,, "B"	106×0·297=31·4
,, "C"	110×0·319=35·1
,, "D"	110×0·321=35·4

the lowest value is found to be that relating to Plant " B." For Plant " D " the value is higher even than with Plant " C," owing to the wages of electricians and fitters for supervision of the electric telpher line. The workmen on the furnace top —work not unattended with danger—are more highly paid than those working on the ground.

There is a wide difference of opinion, both among the blast-furnace owners themselves and among the companies constructing plants, regarding the economy and practicability of the individual systems, and in particular as concerns the type of hoist, whether an inclined hoist or an electric telpher line should be used. It is possible to estimate the initial costs beforehand and in a fairly satisfactory manner. The safety of working depends upon the nature and quality of the construction, the latter item having a great influence on the extent of initial cost and of depreciation. A great deal depends on the skill with which the plant is handled while working and while not working. It may, therefore, be said that the main factor in all transport equipment is the trustworthiness and efficiency of the workmen, technical managers, and unskilled labour, all of whom contribute to effecting economy of working in a plant and to determining the suitability of any plant for definite working conditions.

The trustworthiness of the workmen plays a much greater rôle in plants where many automatic devices are employed than where the entire equipment requires the constant attention of the workmen. Where practically everything is done automatically, the workmen become confident and afterwards indifferent, since they do not realise the possibility of anything failing. Hitches in the working of the electric telpher line, with its many workmen, are still very considerable.

The saving in unskilled labour by the provision of mecha-

nical equipment does not always lead to reduction in working expenses, since, although fewer workmen are required for attending the machines, these must be skilled workmen and more highly paid.

The net value of transporting plants is not determined alone by the reduction in first costs, but also by (1) increase of efficiency, which it is impossible to attain by manual labour alone; (2) independence in the case of strikes, &c., by a reduction in the number of workmen; (3) continually increased improvement of the products in consequence of more expert and accurate supervision of the working processes.

ELECTRIC FURNACES FOR HEATING STEEL.[1]

By ALCAN HIRSCH (New York).

The field of usefulness of the electric furnace for metallurgical purposes is so extensive that it is deemed advisable to limit somewhat sharply that aspect of the subject which is within the scope of this report. The report is limited to a description of electric furnaces used for heating steel for the various kinds of heat treatment, and for forging and enamelling. Details of design, construction, and operation, as determined by the author and his associates in the course of their work, are also described. The essential data only are given, and thus the work is presented from a broad standpoint, an exhaustive presentation of data being likely to lead to confusion. It is thought also that to present the essential details only will make the paper more useful to users of electric furnaces than an exhaustive statement of all the data collected.

In industrial practice and for certain other reasons furnaces can be divided into two classes, this classification applying both to fuel and electric furnaces—(1) furnaces operating above 980° C. (forge furnaces are the main and most important division of this class); and (2) those operating below 980° C. The latter class comprises the furnaces for practically all the heat treating and also enamelling purposes. Although furnaces operating at the lower temperatures will be considered first, it must be borne in mind that a greater part of the principle and theory underlying the construction and operation of moderate and low temperature furnaces also applies to the higher temperature furnaces.

A brief description of the transference of the heat from the heating medium to the metal will first be given. The metal resting on the hearth of the furnace receives its heat in several

[1] Received March 10, 1914.

different ways as follows: (1) from the brickwork in the furnace in contact with the metal; (2) by conduction from the products of combustion; (3) by radiation from the hot walls, roof, and incandescent particles in the burning gases. Generally speaking, in the fuel-fired furnaces these sources delivering heat to the metal are each of the same order of magnitude, but usually the amount of heat passing by means of brick and metal in contact is less than from any other source. If only a small portion of the heat passes into the metal by direct contact with the brick, the rate of heating in all except thin pieces is slow. More frequently than is generally supposed this path of heat transfer is the determining factor in the rate of heating. An excellent example of this kind was brought to the author's attention when die blocks were being heated. In this instance the brick work of the furnace was heated sufficiently to raise the blocks to the desired temperature. Sometimes the fuel was allowed to run sparingly throughout the operation, while at other times it was shut off entirely after the block was placed in the furnace.

The atmosphere of fuel-fired furnaces is exceedingly uncertain. Slight variations in conditions have been found to cause marked variations in results, and as the atmosphere is capable of a great many variations, it is, therefore, difficult to maintain it at a definite composition. It may be oxidising, or it may be reducing in nature. If it be reducing it frequently contains carbon particles. The effects of these various and so frequently varying conditions are, of course, well known. On the one hand, with oxidising conditions the formation of scale occurs, while on the other the danger of local carburisation with sooty flames confronts the operator of fuel-fired furnaces. In the production of high grade steel the condition of hearth atmosphere is, of course, exceedingly important.

The electric furnace provides in many respects just what the fuel furnace lacks, namely, a means for the transference of heat in a very effective manner, and an atmosphere within the furnace which is not only of a very desirable composition, but is also absolutely dependable. This atmosphere is usually of a slightly reducing nature, caused by the presence of carbon monoxide, due to the combustion of the graphite or

carbon resistor, which liberates the electrical energy in the form of heat. In some furnaces having more than one door, or operated with the doors open all the time, the atmosphere may be not reducing but neutral. It is due to these neutral or reducing conditions that the formation of scale is greatly minimised. The author has in mind an electric furnace which was operated with a loss of scale amounting to 80 per cent. or even 90 per cent. less than was occasioned by the employment of an oil-fired furnace for the same work. For special work where an oxidising atmosphere is required, as for instance in enamelling, it is easily obtained in the electric furnace by employing a muffle, the resistors being placed in any desired position on the outside of the muffle.

The question of electric furnaces for temperatures below 980° C. will next be considered. The furnaces employing non-metallic resistors will be given detailed consideration, while the furnaces employing metallic resistors will be but briefly considered.

In the industrial electric furnaces employing metallic resistors the resistor which has obtained the most commercial success employs a resistance wire or ribbon as the heating element. The limitations of these wire or ribbon wound furnaces are, generally speaking, considerable both as regards temperature and capacity. As will subsequently be shown, the temperature and capacity of a furnace are closely interrelated. This interrelation, however, is not of so much consequence in small furnaces where the combined wall and door losses are considerably in excess of the heat actually utilised in raising the metal to the desired temperature. The capacity of the metallic resistor furnace is at most but a very few kilowatts. Furnaces with a larger capacity would be quite out of the question because of the cost of the resistance element. This cost is due to the large amount of wire required and also to the expense of winding. The furnaces are, therefore, limited to productions of small size, and also to rather moderate temperatures, as the danger of burning out due to overheating is always present. For work of an experimental nature small furnaces of this type have, however, proved quite satisfactory.

The furnaces employing non-metallic resistors comprise two types: (1) those where the metal to be heated is in contact with the resistor; and (2) those where the metal to be heated is out of contact with the resistor.

Furnaces of the first class have had but one commercial example, and that has had varying success. This is the bath furnace,[1] which employs a conducting bath of salt, usually barium chloride and potassium chloride, which is fused by the passage of the current through it. The steel to be heated is immersed in this bath of fused salts. This type of furnace appears to the author to be too limited for extensive industrial application, and, therefore, will only be given this brief mention.

Furnaces of the second class, those employing non-metallic resistors, where the metal is heated out of contact with the resistor, hold in the opinion of the author much promise for future development. Recent experience with their operation has demonstrated their suitability to many kinds of work. This type of furnace will, therefore, be considered in some detail.

Generally speaking, furnaces of this class appear to the casual observer very similar to the fuel-fired furnaces, save for the fact that instead of an equipment for burning fuel, an electrical equipment is provided. The electric current is brought to the furnace by suitable cables which are connected with electrodes projecting from the furnace. These electrodes run through the furnace wall and carry the current to the resistor, which liberates, in the form of heat, the electrical energy put into the furnace. This resistor is of a refractory conducting material, such as graphite, usually in granular form, and having a cross section of 30 to 100 square inches, according to the current desired. The resistors are usually placed beneath the hearth, the heat from them being communicated through the hearth to the metal.

For the design of a heat-treating furnace to operate at a hearth temperature of 980° C. or less the following data have

[1] An article on this furnace, by L. M. Cohn, will be found in the *Electrotechnische Zeitschrift*, August 2, 1906.

been found necessary for the preliminary calculation of the chief points of design:

1. The hearth dimensions.
2. The production of metal per unit of time.
3. The maximum amount of metal on the hearth at any time.
4. The desired temperature.
5. Time for charging and discharging.

The first step in the design is to determine the situation of the resistor, but this depends somewhat on the physical characteristics of the material employed for the resistor. Resistors which are placed in the furnace in granular or similar form have been much more extensively employed in the larger furnaces than any other kind. Rods of graphite and also of other materials, metalloids as well as the characteristic non-metallic materials, have been tried for use as resistors. Although some of these will undoubtedly find commercial fields, nothing has as yet proved satisfactory in this direction. Attention, therefore, will be confined to granular or similar forms. Of these granular graphite has given the most satisfactory results.

For the usual class of electric furnace work the situation of the resistor is logically in the base of the hearth. For a small proportion of the furnaces, however, resistors can be advisedly placed elsewhere as well as in the base of the furnace. These positions are along the side of the hearth and possibly even along the top. Furnaces requiring resistors in these latter positions are those taking piles of sheet metal or pots of materials and the like. However, with one layer of pieces, which rests directly on the hearth, the situation of the resistor had best be exclusively in the base. The reasons for this are: (1) heat has a tendency to ascend rather than to descend; (2) contact between hot brick and the metal to be heated facilitates heating; (3) the design is facilitated, as will be subsequently shown. When the resistors are placed in the base of the furnace they are put in troughs of suitable refractory material and usually, but not always, covered partly or completely with brick or tile, which forms the hearth.

The shape of the resistors can be exceedingly varied. They

may be straight, U, S, T, or Y-shaped. They may be electrically connected in a number of ways. They may be connected in series, or parallel, or some in series and others in parallel. They may be permanently electrically connected, or they may be capable of various electrical arrangements by switching.

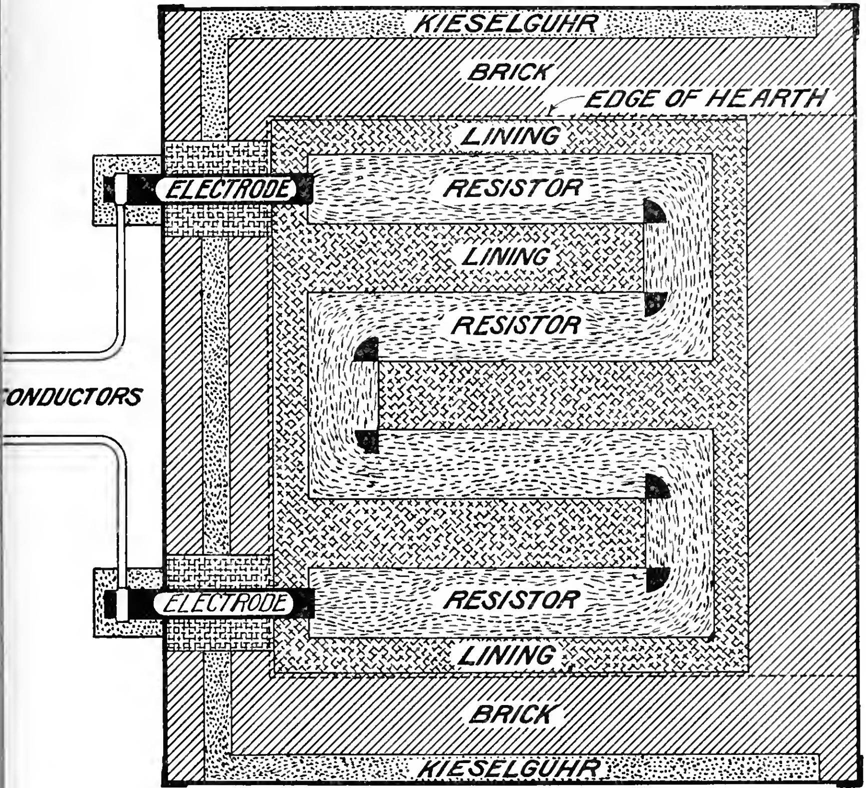


FIG. 1.—Serpentine Resistor employed in fairly large Furnaces.

With this brief resumé of the possibilities, furnaces having resistors permanently connected electrically will be described first. In these furnaces the resistors are constructed so that they must be operated in the same way from the point of view of electrical arrangement at all times. In practically all cases of this class either a serpentine or U-shaped resistor is employed, but two or more straight resistors connected

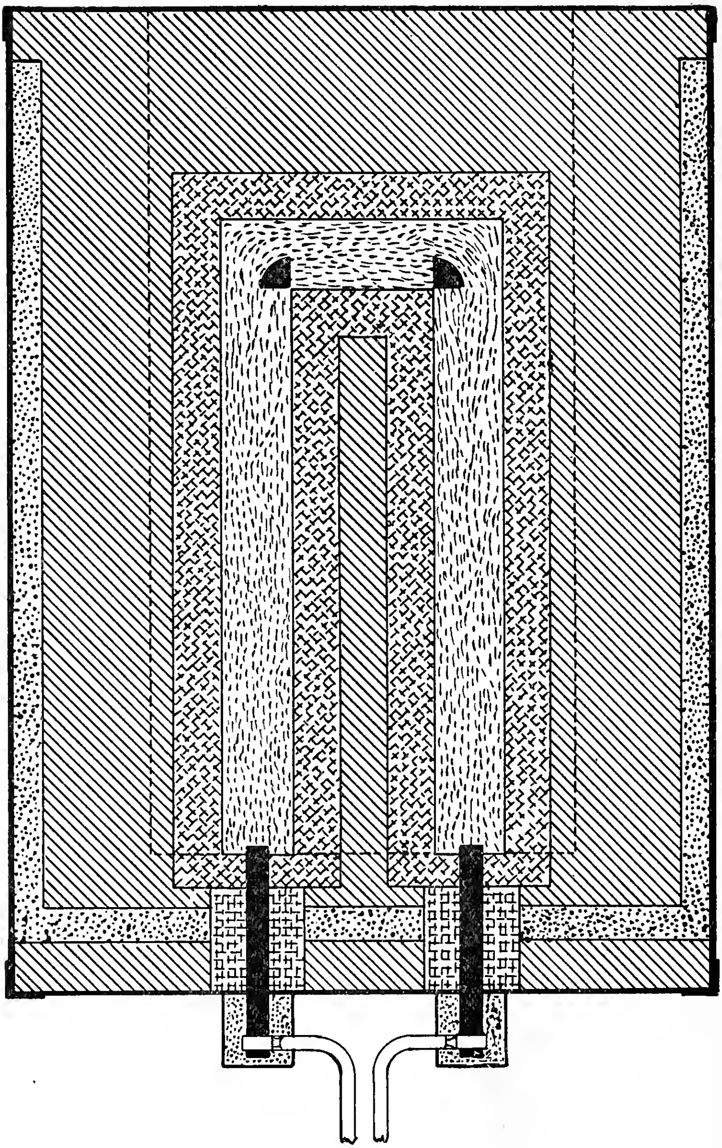


Fig. 2.—U-shaped Resistor for smaller Furnaces.

either in series or in parallel may be used instead. Fig. 1 shows the serpentine resistor which has been employed in moderately large furnaces only, it being impossible to adapt this type to the smaller furnaces. Fig. 2 shows the U-shaped resistor which has been employed in furnaces of any size, but has certain limitations, which will be considered later.

TABLE I.

Temperature of Operation.		Kilowatts to raise 1 lb. of Steel per Hour from 60° F.	Wall Loss in Kilowatts per Sq. Foot outside Surface.	Door Loss in Kilowatts per Sq. Foot.
Degrees F.	Degrees C.			
1000	538	0·0366	0·035	0·6
1100	594	0·0460	0·039	0·9
1200	649	0·0527	0·042	1·3
1300	704	0·0597	0·046	1·7
1400	760	0·0668	0·049	2·3
1500	815	0·0733	0·053	3·0
1550	843	0·0765	0·055	3·5
1600	870	0·0796	0·056	3·9
1650	898	0·0840	0·058	4·5
1700	926	0·0881	0·060	5·0
1750	954	0·0926	0·062	5·6
1800	982	0·0970	0·064	6·3
1850	1010	0·0994	0·065	7·1
2400	1316	0·1220	0·085	20·0

There are several ways to determine the electrical load for a given furnace, but only one can be deemed sufficiently practical to be dealt with in this report. Only furnaces of 200 kilowatts capacity or under will be considered, and it may be said that furnaces for heat treating larger than this are very rarely found. The electrical load is the sum of three factors: (1) the electrical equivalent of the amount of heat necessary to raise the metal to the required temperature; (2) the electrical equivalent of the loss of heat through the walls; and (3) the electrical equivalent of the loss of heat through the door, in consideration of the fact that this is alternately opened and closed. The power factors of furnaces of this size are from 97 to 99 per cent., so can be neglected in the calculation of the necessary wattage. From the data in Table I. the watts necessary to

operate any particular furnace may be very easily and closely approximated. The door loss shows the watts passing through the door opening if the door be open all the time. If the door be open only half the time, only half the amount given in the table should be taken, and so on in proportion. The wall upon which the wall loss figures are based is 12 inches thick. It consists of 9 inches of silica brick and 3 inches of kieselguhr. In actual practice this has been found to be a convenient standard to take.

As an example of the method of calculation, the electrical load for a particular furnace will be determined. Assume the following data for this illustrative case:

1. Outside dimensions, 4 feet by 4 feet by 6 feet long.
2. Production, 500 pounds of steel per hour.
3. Temperature, 926° C.
4. Door, 2 square feet, open 40 per cent. of the time.

This furnace had a total outside area of 128 square feet. The table shows a wall loss of 0·060 watts per square foot, making a total loss of 7·68 kilowatts for the walls, top, and base. The door loss would be 10 kilowatts if the door were open all the time, but it being open but 40 per cent. of the time, the loss is 4 kilowatts. As 0·0881 kilowatts are required to raise one pound of steel from 15° C. to 926° C. in one hour, 500 pounds per hour would require 44·05 kilowatts. Thus it will be seen that this furnace will require 55·7 kilowatts for operation. No factor of safety need be applied to this figure if the conditions selected are at the maximum. On the contrary, if these are normal operating conditions a factor of safety should be applied according to the possibilities of greater demands being made on the furnace.

The number of kilowatts necessary for operation having been determined, the length of the resistor is approximated in order to determine the voltage. With granular graphite[1] experience has shown that the most satisfactory voltage is $1\frac{1}{2}$ volts per inch length of the resistor. From this voltage and the wattage as computed above, the number of amperes may easily be determined.

[1] Artificial graphite averaging $\frac{1}{8}$-inch mesh, but containing no fine powder.

The electrical resistance of a resistor in a furnace cannot be sufficiently closely predicted to ėnable the size of the resistor to be calculated with any very great degree of certainty. Of necessity, therefore, the exact voltage which will be required for a furnace to take a certain number of kilowatts can only be determined approximately. A provision for obtaining various voltages is therefore necessary, and a transformer with several taps is ordinarily employed for this purpose. However, it is perfectly possible to provide a variable voltage generator for the same purpose. Owing also to the fact that the precise production of steel for a given furnace cannot be very closely ascertained, and also owing to the fact that in most cases different productions at different times are desired, it is absolutely necessary that provision be made for altering the kilowatt input at the will of the operator.

The usual and satisfactory method of meeting these requirements appears to be the employment of a transformer with ten to fifteen taps. Usually thirteen is a satisfactory number, having a range of voltages on the secondary from a minimum equivalent to one volt per inch in length of the resistor to a maximum equivalent to two volts per inch in length of the resistor. The various taps on the transformers used in most instances have given voltages which are in arithmetical progression, but it is the opinion of the writer that a progression of voltages in unequal steps is best suited for the work. For the purpose of making provision for the uncertainty of the resistance of the resistor, the voltages would logically be chosen in arithmetical progression. For purposes of regulation, however, since the kilowatt input increases as the square of the voltage, it would appear, from this point of view, that the voltage steps should be graduated so as best to meet this condition. The two conditions must be met, and the most satisfactory arrangement is to give the steps such a progression that the difference of the kilowatt input on adjacent taps in the higher voltages will not be so very much larger than on the adjacent taps on the lower voltages. Accordingly, a satisfactory range of potentials on a transformer with thirteen taps would have voltages equivalent to the following, per inch

length of the resistor: 1·00, 1·10, 1·20, 1·29, 1·38, 1·47, 1·56, 1·64, 1·72, 1·80, 1·87, 1·94, 2·00.

A method for obtaining this regulation and adjustment without the use of a transformer has been devised in the author's laboratory very largely through the work of Mr. Richard S. Bicknell. In this type of furnace several resistors are employed which are not permanently electrically connected, and, by means of suitable switches, may be connected in various ways while the furnace is in operation. They may be arranged in series, parallel or in such combinations of electrical arrangements as are necessary to effect the desired regulation. In other words, this is regulation by altering the resistance of the resistor as contrasted with the aforementioned method, where regulation was effected by altering the voltage impressed upon the resistor. As will be subsequently shown, this type of regulation is particularly adapted to furnaces having 10 square feet of hearth area or over. An example of a furnace capable of such regulation is shown in Fig. 3. With these four resistors in this particular furnace it is possible to obtain 110 inches in length of resistor, or the equivalent of same, in the circuit at one time, and 220 inches in length of resistor at another. A large number of intermediate lengths of resistor between this maximum and minimum figure may also be placed in operation. This particular furnace is designed to operate on 220 volts, and it will readily be seen that the maximum voltage obtainable per inch of resistor is two volts and the minimum is one volt. A surprisingly large number of intermediate lengths of resistor are obtained by employing the four T-shaped resistors as shown. The length of the resistor is, of course, merely another way of stating the resistance of the furnace. These T-shaped resistors have each three unequal legs. Resistors A and D are similar and B and C are similar, but A and B have corresponding legs of different lengths. The resistance of the furnace resistors for a number of intermediate steps is made by connecting two legs in parallel in instances when a low resistance is desired. When a high resistance is wanted the resistors are run in series, the current passing through the longest legs only. By properly proportioning the legs, it will be seen that

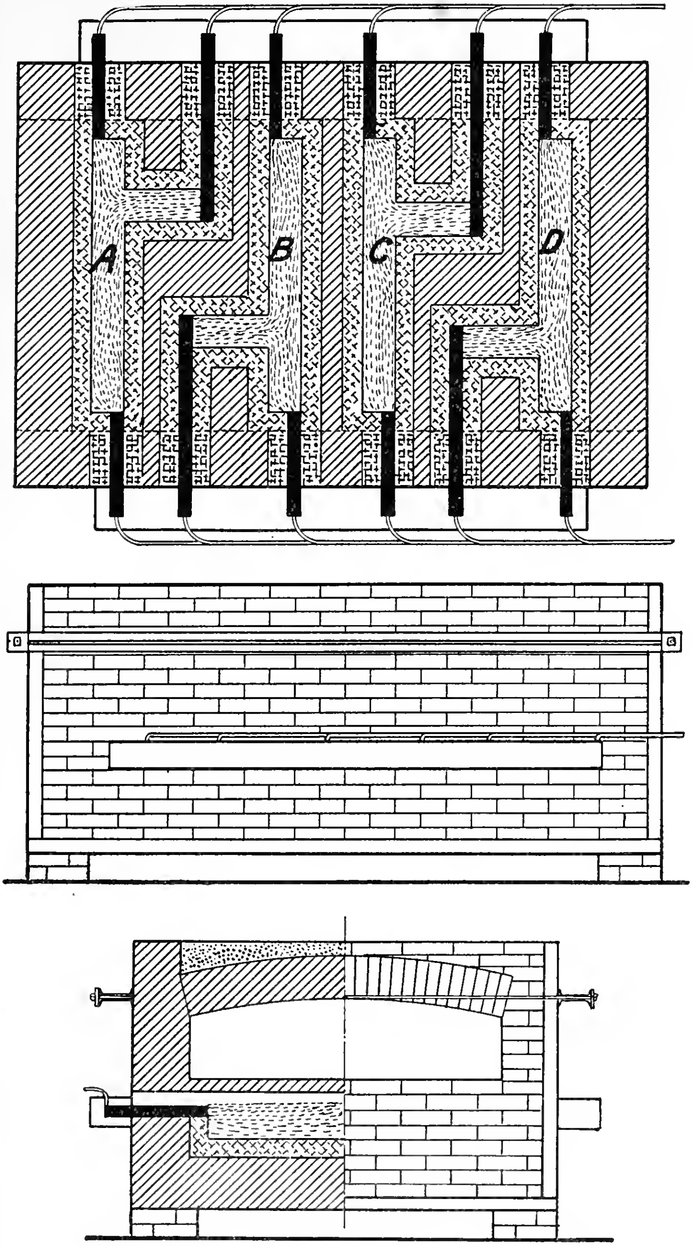


FIG. 3.—Method of Furnace regulation.

the number of intermediate steps for the purpose of regulation may be made as large as desired.

It is, of course, possible to combine these two methods of regulation, namely, by voltage and resistance, having a few steps on the transformer and having one or a few resistors capable either of being arranged in series or parallel. Such a furnace is shown in plan in Fig. 4, and is quite suitable for small furnaces of from 4 to 10 square feet hearth area. The construction of the resistor as shown in vertical section would be similar to that shown in Fig. 3.

The length of the resistor having been determined, the width and depth must be found. This determination applies to both types of furnaces where either method of regulation is employed, either altering the voltage or the resistance.

It has been found that a resistor placed beneath the hearth can advantageously be composed of two layers of materials. The upper part is made of granular graphite and the lower of some material of lower electrical conductivity than graphite, such as charcoal. This lower layer of charcoal takes a smaller part of the current than the upper layer of graphite, and therefore the bulk of the heat is liberated near the top of the resistor. This method seems to protect the part of the lining upon which the resistor rests sufficiently well, not only to warrant its use, but to make it absolutely necessary in the case of furnaces operating close to or above 980° C. A resistor consisting half of charcoal moderately tamped by hand and half of graphite gently tamped in forms a very satisfactory resistor. The resistance of an inch cube consisting in the upper half of granular graphite (pieces three thirty-seconds to one-eighth inch), and the lower half of hard wood charcoal, placed in accordance with the method described above, is approximately 0·125 ohms at 925° C. The current necessary having been computed for the normal running condition of $1\frac{1}{2}$ volts per inch length of resistor the area of the cross section of the resistor may thus be easily determined.

The width and depth of the resistor should be such that as much heat as possible is liberated in the desired direction. For resistors in the hearth this direction is, of course, upward. According to the theory, therefore, the logical shape of

resistors of this sort would be as wide as possible and quite shallow. This section, however, is not at all feasible for several reasons. The resistor burns away more rapidly when it is wide, and it is more difficult to spread the graphite on a wide resistor when it is replenished. Wide resistors require more lining, and, as will be shown, the expense of the lining is a relatively important item in the cost. When wide resistors are made to run at right angles the current has a tendency to flow across the interior corner in much higher intensity than at the exterior corner. Sometimes carbon or graphite blocks have been placed in the resistor at the corners for the purpose of reducing this local effect. This, however, is not a very good remedy, as the heat liberated in any event is not so great per unit area of the resistor in the corner as in other parts of the furnace. The cross section of the resistors should therefore be made about square, or wider than the depth by a small amount. If possible, the resistors should not be narrower than their depth, but it is impossible to observe this requirement in all cases. Resistors less than $2\frac{1}{2}$ inches wide should not be used. They should be not less than 6 inches deep and preferably about 7 inches, except for the resistors over 10 inches wide which can be made 8 inches deep, but more than this is likely to lead to excessive heating in the base of the furnace.

The designer frequently has the opportunity of employing one large resistor or two smaller ones to do the same work. Small resistors less than 3 inches wide should be avoided because slight variations in the shape have a more marked effect on their resistance than in the case of the large resistors. It is much better, as a rule, to employ a short resistor 4 or 5 inches wide in place of a correspondingly longer one $2\frac{1}{2}$ or 3 inches wide. On the other hand, too large resistors are also to be avoided. Since the thermal conductivity of graphite is rather low it will readily be seen that large resistors are much more likely to become excessively heated in their centres than the small resistors. Resistors of 6 to 9 inches in width are to be used whenever possible, and resistors of this type, 12 inches wide and 8 inches deep, are about the maximum size for resist-

ance furnaces used for heating steel. This is decidedly too large, however, for any heat-treating work, but the author mentions it merely to give an approximation of the maximum limitation of this type of furnace. This 12 by 8 inch resistor would carry 1000 amperes, and a number of resistors could be arranged in a furnace so as to liberate 16 kilowatts per square foot of hearth. This is equivalent to a production of about 110 pounds of steel heated to 925° C. per hour per square foot of hearth under the usual conditions. This production is not only more than is usually desired, but is far too much for good work. Experience has shown that a maximum production of about 50 pounds per hour per square foot of hearth at 925° C. is all that can be expected in electric heat treating furnaces.

The temperature and the production of steel from an electric furnace are mutually dependent. The heat liberated in the resistor, if not taken up by the metal, will occasion a rise in temperature of the furnace. The larger the electrical capacity per unit area of hearth, the greater the effect on the temperature by alteration in the production. It is for this reason that productions of over 50 pounds per hour per square foot of hearth should be avoided. With moderate capacities of 4 or 5 kilowatts per square foot of hearth area (equivalent to a production of 30 to 35 pounds of steel per hour to 925° C.) variations in production have but very little effect on the temperature. The heat capacity of the resistor lining and brick work in furnaces of this size is ample to compensate for changes in production, so that the temperature remains practically constant. A furnace designed for a normal running load of 4 kilowatts per square foot of hearth (with 1½ volts per inch length of the resistor) will prove very satisfactory. The uniformity of temperature on the hearth in furnaces employing the T-shaped resistors shown in Fig. 3 is quite remarkable, but even with the U-shaped or serpentine resistor a temperature variation of less than 5° C. from the desired temperature is to be expected at any point of the hearth.

Enamelling furnaces fall into the same category with the heat-treating furnaces. Although they are larger in size

they are not correspondingly large in electrical capacity. In enamelling furnaces, a part of the resistors should be placed along the sides of the muffle, but about three-quarters of the kilowatt input should be liberated in the base. Resistors, when placed along the sides of the muffle, should be small, 10 to 20 square inches in section, and should consist entirely of graphite. The lining of such a resistor is usually designed so as to form part of the interior wall of the muffle.

With respect to the class of furnaces heating to over 980° C., a number of furnaces have been constructed and tried for various lengths of time, but a durable furnace, certain in operation, has yet to be produced. Most of the experiments have been made with furnaces with a single resistor about half graphite and half charcoal, as mentioned above. These resistors have been made about 18 inches wide, and placed in a trough of a mixture of refractories, the basis of which is firesand. The metal to be heated, consisting of steel bars for forging, has been placed directly above the resistor, but not touching it, and heated to about 1315° C. In order to effect a production similar to that of a forge furnace of the same size fired by oil, the temperature of the resistor has to be above 1595° C. For this temperature it seems impossible to construct a furnace which will have a very long life. In the course of a few weeks the lining or the bricks will have fluxed to some degree and rebuilding will be found necessary. A lining of practically pure silicon carbide brick might withstand these conditions, but it is questionable if a refractory any poorer than this would be satisfactory. The electrodes, too, are difficult to hold in place without costly supports, which might have to be water-cooled. These furnaces, which have been used for heating metal for forging, have shown, in some instances, good economy. A current consumption of 370 kilowatt hours per 2240 pounds of metal on a 100 kilowatt furnace has been recorded. In general, the type of construction on these furnaces was similar to that shown in Fig. 2 with the exception that for the U-shaped resistor was substituted a single straight one, running from one end of the hearth to the other. For work at forging temperatures a furnace employing a graphite resistor does not

seem capable of becoming a commercial reality unless a very unique lining can be developed.

The author has given considerable thought to this important field of electric furnaces for forging, and has evolved a furnace which appears to eliminate most of the difficulties encountered. This furnace is as yet only in the experimental stage, although it appears to offer attractive commercial possibilities. It is of the arc type, and thus many of the difficulties inherent to the resistor furnace at once disappear. As there is no resistor there is, of course, no resistor lining. The metal is placed on the hearth, and is heated directly by the arcs, the bases of which play a few inches above the metal to be heated, thus obtaining a high thermal efficiency. The arcs are deflected by means of an auxiliary electrode which spreads this flame so as to distribute the heat comparatively evenly, and also serves to protect the roof of the furnace. The roof, if built of silicon carbide brick, will have a long life. As the electrical equipment is placed above the hearth it is easily accessible, and may be removed by a crane, and a new top placed on the furnace in a very few minutes. As arcs of a few kilowatts are difficult to operate, it would probably be necessary to build a furnace capable of a very substantial production. The author hopes that definite commercial data regarding this furnace can be secured very shortly.

The design of furnaces from a structural standpoint and with a view to determining the best materials of construction will next be considered. Fig. 3 shows a heat treating furnace of 125 kilowatts capacity under the normal running load. It has a maximum capacity of 175 kilowatts. The hearth is 5 feet wide and 9 feet long inside.

A very satisfactory furnace wall has been found to consist of two bricks laid so as to make 9 inches and with 3 inches of kieselguhr. This kieselguhr may be placed between the bricks forming a vertical channel, or may be placed outside the bricks, in which case sheet metal is employed for the outside of the furnace to hold the kieselguhr in place. Asbestos mill-board may be used in place of sheet metal, but the heat losses with mill-board are not appreciably less than with metal, and, of course, asbestos is not so durable. Furnaces may be well

insulated on the top and sides of the hearth, but care must be observed not to insulate the base too well. It must be recognised that in electric furnaces the heat is evolved within the brick work, and consequently the evolution of heat differs somewhat from that in fuel-fired furnaces. Hence, the furnace should be set clear of the floor, with only about 15 inches of brick allowed up to the lining on the base of the resistor. Twelve inches is quite sufficient for this dimension for furnaces working above 980° C. Good fire brick should be employed; silica bricks serve excellently for this purpose. These bricks contain about 95 per cent. silica and a little lime. Good masonry work, and particularly well-constructed arches, will be much the cheapest in the long run. The principles of oil-furnace design are, of course, applicable to these types of electric furnaces.

It is most important to select the proper refractory for the lining of the resistor. The lining is usually in the shape of a trough, the resistor being placed in it. The lining material must have a high melting point; it must not have a high vapour pressure at its operating temperature; it must not react chemically with the hot resistor on one side or the brick on the other; and it must not become soft or "mushy" at the operating temperature. Its electrical conductivity at the operating temperature must be considerably less than that of the resistor, and it must be relatively cheap.

The operating temperature of the lining is rather high, normally a few hundred degrees higher than the hearth temperature, but for various reasons the maximum temperature obtained in a lining may be a thousand or more degrees higher than the normal operating temperature. The reason for obtaining these high temperatures in the lining may be due to neglectful operation or an attempt to get an extraordinarily large production at a particular time. It is, therefore, necessary to employ a lining having a high factor of safety as regards the temperature. It is exceedingly difficult to find a material which meets these requirements at a temperature of 2000° C. (3632° F.). It must be remembered that although refractories of high melting points are available, the addition of the necessary binder, even though in small amount, may lower

the fusing point of the lining very materially. The following substances[1] have high melting points:—

Uranium carbide	2425° C. (4396° F.).	
Vanadium carbide	2750° C. (4982° F.).	
Calcium oxide	1995° C. (3623° F.).	Boils 2015° C.
Aluminium oxide	2020° C. (3668° F.).	
Uranium oxide (U_2O_3)	2176° C. (3946° F.).	
Zirconium oxide	2500° C. (4532° F.).	

In addition, two other substances should be mentioned. Glucinum oxide has a high melting point, and boron nitride shows no sign of sintering at 3000° C. (5432° F.) Magnesium oxide begins to vapourise under atmospheric pressure at 2009° C. (3650° F.). All metallic oxides are somewhat acted upon by hot carbon, and as the speed of reaction approximately doubles for every 10° C. rise in temperature, at electric furnace temperatures this chemical action is often sufficient to deteriorate considerably if not entirely to destroy the lining. At about 2000° C. (3632° F.) magnesia is rapidly attacked by carbon.[2]

The electrical conductivity of lining materials, especially metallic oxides, increases very rapidly with the temperature. Materials which are excellent insulators at room temperature become good conductors at electric furnace temperatures. A slab of alundum (fused alumina) had a specific conductivity[3] at 1600° C. (2912° F.) about fifty thousand times as great as at 20° C. (68° F.). In the author's experience silicon carbide firesand offers advantages over other refractory materials for the linings of furnaces considered in this paper. A mixture of 85 parts of silicon carbide firesand and 15 parts of water glass (38° Be.) forms a good lining when well baked in the furnace. A slightly better lining can be made with the above mixture for the outside of the trough and pure silicon carbide with the water glass in the same proportions for the inside next to the resistor. At operating temperatures it is a much poorer conductor than graphite, and there is

[1] Ruff and Goecke, "Fusion and Volatilisation of Highly Refractory Materials." *Zeitschrift für Angewandte Chemie*, vol. xxiv. p. 1459 (1911).

[2] O. P. Watts, "Action of Carbon on Magnesia." *Transactions of the American Electrochemical Society*, vol. xi. p. 279 (1907).

[3] E. F. Northrop. *Metallurgical and Chemical Engineering*, vol. xii. p. 125 (1914)

practically no chemical action between it and either carbon or silica brick with which it is in contact. Silicon carbide begins to decompose at about 2300° C. (4172° F.) into silicon and carbon, of which the former vaporises, but it has given excellent service over a considerable period of time. A silicon carbide lining, properly built in a heat treating furnace designed to give a hearth temperature of 1010° C., should not need renewal more often than once in six months, and frequently such linings last much longer. It will be seen with these materials, however, that linings are relatively expensive items in furnace construction, so the firesand is probably the most economical to use, particularly if 925° C. is the maximum hearth temperature desired. The lining is put in place with the assistance of wooden forms, allowed to dry, and when the furnace is started it becomes well baked.

The author ventures to suggest that the question of linings for this type of furnace offers an attractive field for research, and sincerely hopes that scientific work along these lines will be made by investigators.

The electrodes are placed in the furnace imbedded in a mixture consisting of silicon carbide 90 parts, and tar (melting point 38° C.) 10 parts. They project from the furnace wall about 6 inches into a box. This box is made of asbestos mill-board, with a framework of small angles attached to the furnace. The box has no top. The leads are run into the box from the top, and are clamped to the electrodes. The box is then filled with kieselguhr. The electrodes may be either of graphite or carbon, but preferably the former. The size of the electrodes may be calculated by the well-known methods,[1] and either square ones or round ones may be employed.

The switchboard has a main switch, and a radial switch with a number of points if a transformer is used. The switching may be accomplished on the high tension or the low tension side of the transformer, as is desired. If regulation is effected by altering the resistance, with a furnace such as is shown in

[1] The author believes the best method for determining the proper cross section of electrodes is contained in an article by Carl Hering: "Empirical Laws of Furnace Electrodes," *Transactions of the American Electrochemical Society*, vol. xvii. (1910). Table VI. in this paper may be employed very satisfactorily for the calculations.

Fig. 3, knife switches alone are used, as no transformer is employed. The resistors are thrown in or cut out by single bladed knife switches, according as desired. An ammeter is employed in all cases unless the primary tension is too high to warrant its satisfactory operation. The ammeter is, of course, always placed on the primary side of the transformer. If an ammeter cannot be used a wattmeter may be employed, or may even be used in preference to an ammeter if desired.

The electrical wiring should be very carefully done and strongly constructed. The chief precaution to observe is to insulate all conductors of current, and to arrange them in such a way that the furnace heat will not injure them. In most cases it is preferable to run the conductors down from the electrodes along or beneath the floor to the switchboard. The switchboard, of course, must be accessible to the operator of the furnace, and is preferably placed by the side of the furnace near the end provided with the door.

The operation of the electric furnace of the graphite resistor type is found to be very simple. A new furnace is started up slowly, the voltage equivalent to one volt per inch length of the resistor being applied for about twelve hours. At the end of this time it may be brought up to temperature by gradually raising the voltage per unit length of the resistor. The metal is passed through the furnace, the operation being quite the same as in the fuel-fired furnace, and with a very little experience the proper load for each particular job may readily be ascertained. If a change in the production of steel occurs in the furnace, or a change in temperature is desired, it is advisable to raise or lower the kilowatt input, as the case may be, about fifteen or twenty minutes before the change occurs. Otherwise, failure to get the production on the one hand, or failure to get the temperature on the other, may be the result.

When the furnace is to be shut down the current may be turned off fifteen or twenty minutes before the last piece of metal is removed from the furnace. The furnace is then closed, and as it is very hot, it will take but a short while to heat up after the usual over-night shut-down of fourteen hours. The time to heat up after such a period is from twenty to thirty

minutes. To heat the furnace up from the cold requires about one hour.

As previously stated, the resistor partially burns away and must be replenished. This should be done at intervals of about seventy hours of operation on furnaces operating from 925° C. to 980° C., but furnaces operating on lower temperatures will run for longer intervals without replenishing. At 925° C. hearth temperature the consumption of graphite is approximately 0·01 pound per kilowatt hour. The graphite may be charged through small port-holes located in the sides of the furnace by means of long-handled scoops. It is then raked down with a small rake adapted to the particular resistor.[1] In some instances the resistor runs uncovered or partially uncovered along the sides of the hearth in the interior of the muffle. In this case the graphite is shovelled in through the furnace door. The proper amount of graphite to be used will be readily found by a few trials, noting the position of the switch before and after charging for a given load.

Although the furnace has been designed with the idea of supplying enough current to heat the metal and to make up the losses of radiation, &c., the superintendent of the heat treating department is very likely to consider the furnace from a standpoint of efficiency. This may be expressed in percentages or kilowatt hours per unit of production. Table II. shows the relation between these two methods of expressing efficiency.

In general, the larger the production of metal in a particular furnace, the greater the electrical efficiency. Too high production, however, usually means difficulties in control, and, with very high productions, there is danger of overheating should there be slackening in the production without a corresponding change in the kilowatt input being made. The aim to make a production at a rate equivalent to 4 or 5 kilowatts per square foot of hearth, and also at 65 to 75 per cent. efficiency is an excellent one. When the cost of current is rather high, work which necessitates a production

[1] The upper surface of the resistor should be raked as level as possible, but it is better to have it slightly concave laterally than convex.

at a lower efficiency than 60 per cent. should be transferred to a smaller furnace if the shape of the pieces permits. On furnaces under 30 kilowatts capacity these figures do not apply, as the efficiency on such small furnaces is very much less than on the moderate size ones of 50 to 125 kilowatts.

TABLE II.—*Showing the Number of Kilowatt-hours required to raise 1 Ton* (2240 *lbs.*) *of Steel to various Temperatures at Efficiencies varying from* 50 *to* 100 *per cent.*

Rise in Temperature in Degrees.		Efficiency per Cent.					
Fahr.	Cent.	100	80	70	60	50	
950	528	89	111	127	148	178	Kilowatt-hours per ton (2240 lbs.).
1050	584	103	129	147	172	206	
1150	639	118	147	168	196	236	
1250	695	134	167	191	223	267	
1350	750	150	187	214	249	299	
1450	806	164	205	235	274	328	
1500	834	171	214	245	286	342	
1550	861	178	223	254	297	356	
1600	889	188	235	268	313	376	
1650	916	197	246	282	328	394	
1700	945	207	259	296	345	414	
1750	972	217	271	310	362	434	
1800	1000	222	278	318	370	445	
2350	1306	272	340	388	453	544	

As the regulation is accomplished by simply throwing over the switch, the furnace may be regulated by the workmen. The wiring, of course, must be arranged so that it is impossible to short-circuit the line by means of the switches. The workmen, however, must be instructed not to run the furnace on a voltage equivalent to 1·8 or 2 volts per inch in length unless the production really warrants it. Otherwise, between charges overheating may sometimes occur while the furnace is empty. To provide against overheating in this manner, fuses should be carefully selected of low amperage, which is determined by the maximum rate at which the work should be done. This precaution is to be observed particularly on furnaces where productions are varying widely from day to day. For temperatures over 980° C. it might be advisable to equip the furnace with a pyrometer constructed so as to

operate a circuit breaker when the maximum desired temperature is reached.

In order to determine the number and size of furnaces for an installation a careful inquiry into the nature and quantity of the production is necessary. The maximum and minimum productions must be met with as high efficiency as possible for the various productions. Frequently a moderately large furnace to operate all the time, accompanied by a smaller one to be operated as needed, is much more economical from a point of view of current consumption in the long run than one furnace capable of the maximum production. Care must be observed not to make the furnace too large for the sake of being on the safe side. A furnace so large that it takes 10 per cent. more current than a smaller one exactly suited to the work would waste enough current in the course of six months, or a year at the outside, to pay for a complete new installation.

Sometimes the labour requirements determine the size of the units. Two men on a single furnace might not be able to accomplish so much as they would if operating two smaller-sized furnaces. If a case of this sort arises the decreased efficiency in two furnaces must be carefully compared with the saving in labour in the particular case.

In the selection of the type of furnace for the particular work, if 10 square feet or more of hearth area are required, a furnace regulated by the resistance method (Fig. 3) is certainly to be preferred. This furnace costs about half as much as the furnace equipped with a transformer, and has a much more uniform heat liberation in the hearth. Electric furnaces with resistance regulation, including all the electrical equipment, cost about the same for installation as a good oil furnace, and frequently somewhat less if a blowing equipment installation for that furnace is included. As a rule, these furnaces operate on a higher voltage than do the furnaces having a special transformer, and so a saving in copper for the conductors is sometimes effected. They can be designed to operate on the standard voltages, 220 volts being very satisfactory, and, of course, can operate on either direct or alternating current. The larger furnaces can be

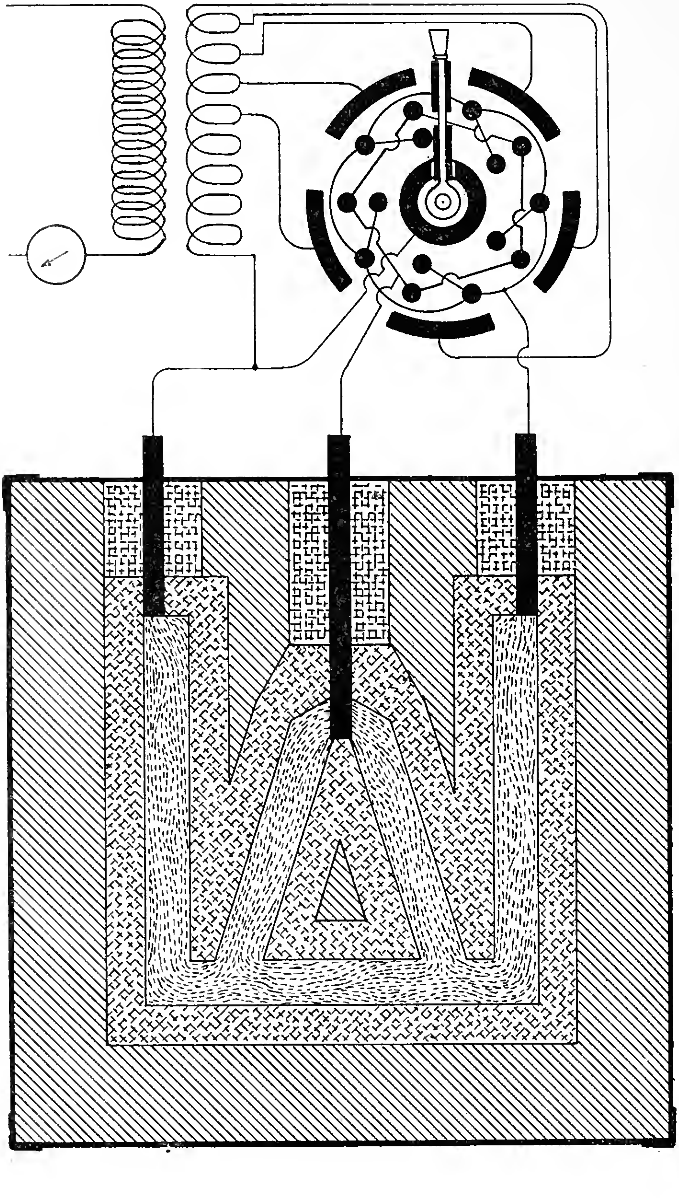


Fig. 4.—Regulation Appliances for small Furnaces.

built to operate on two or three phase lines, but those taking 100 kilowatts or less are best constructed to operate on either single phase or direct current. For the small furnaces a regulation by means of voltage is best employed with a transformer having a secondary with several taps, as before mentioned, either with or without the resistance regulation in conjunction with it, as shown in Fig. 4.

The extent of use of the electric furnace for heat-treating depends very largely on the cost of current. Fortunately, in this connection, the resistance furnaces have a remarkably steady load. The starting load is somewhat less than the running load. In a large number of cases the mean running load is found to be between 80 and 90 per cent. of the maximum demand. Under these circumstances, particularly with operation extended into or through the night, current can usually be furnished for a low figure. The price of ½*d.* per kilowatt-hour is frequently sufficient to warrant the employment of the electric furnace in place of oil on the ground of cheaper cost of operation alone. Current for 0·4*d.* per kilowatt-hour frequently proves as cheap as any method of firing when all factors are considered. Among these factors, most of which have been duly considered, might be mentioned a lower labour charge which is usually effected by the introduction of the electric furnace. The furnace is conducive to high outputs on account of the fact that it is not so uncomfortable for the workmen as the fuel-fired furnaces. In addition to the fact that it is relatively cool, the elimination of all smoke and dirt, and the accompanying difficulties with the products of combustion, the electric furnace is a much more satisfactory furnace from the workmen's standpoint than has ever before been produced.

The author wishes to express his appreciation of the assistance of his associate, Mr. Richard S. Bicknell, both in the study and design of these electric furnaces, and in the preparation of this report.

ROTARY BEND TESTS, ALTERNATING BEND TESTS, AND REPEATED SHOCK TESTS.[1]

By E. NUSBAUMER (Paris).

INTRODUCTION.

The property of sudden fracture which certain metals display under insignificant stress has led to the study of properties other than the static constants of tension or of bending, for the elucidation of the character of such metals. For the last few years resistance to dynamic stresses, and in particular to dynamic bending stresses, has likewise been taken into consideration in this connection, the new test receiving the generic name of the impact test.

In spite of the opposition which the impact test has encountered, it appears to be taking its place more and more in current works practice. Certain motor-car factories insist that a test-piece for impact testing shall be taken from the vicinity of every part in a chassis which may be subjected to shock and the fracture of which might lead to serious accidents. Thus the impact test would appear to furnish a superior guarantee than the tensile test, against the more or less explicable breakages to which certain parts, such as axles, steering-knuckles, and steering-levers may be subjected in service.

It is nevertheless beyond any doubt that the motor-car parts referred to above have much more frequently to resist a series of repeated shocks or vibrations, or, generally speaking, relatively weak stresses, of whatever their nature, repeated a very great number of times, and often in two opposite directions, than a sudden, or, in particular, a violent impact. Besides, in the latter case no surprise is experienced at a sudden breakdown. It is equally beyond all doubt that

[1] Received March 13, 1914.

pieces which have exhibited proper resistance to shock, even when they have been inspected with the greatest care, sometimes break during use in what is, apparently at least, a sudden manner, and while working under loads which must be decidedly lower than their elastic limits. This has given rise to the notion of studying the way in which metals behave under tensile, compressional, and bending stresses, or under repeated impact (the so-called Wöhler tests and the tests carried out by Guillet and Boudouard, by Arnold, and by Stanton and Bairstow).

These tests, carried out from different standpoints, according to very different methods and on widely differing metals, have not always given very concordant results. The author has endeavoured, in the present investigation, to carry out these tests systematically on metals as capable of comparison as possible, in order to ascertain if the conclusions that might be drawn from each of them would be comparable with those drawn from all the others. Secondly, an endeavour has been made to ascertain whether the simple impact test, which is cheaply carried out and better known than the former tests, would give results of the same order, as they do, and whether the information it furnishes may serve as a safe guide in works practice, this second object of the investigation being, in the author's opinion, the most important.

The investigation has therefore been undertaken with an essentially practical object, and in the details connected with it the author has invariably sought to realise those conditions which most closely approximate to those of works practice. The investigations have certainly not led to all the results that could have been wished, because the kind of test dealt with here is highly tedious, and having been undertaken in the midst of the routine duties to which the author was chiefly devoted, have not always been capable of being followed up by him quite as he would have desired. He believes that he has nevertheless arrived at certain interesting results which will be detailed in the following pages.

After rapidly sketching the history of the subject, the materials employed, the apparatus made use of, and the results of the experiments will be described, ending with the

statement of certain propositions which appear to the author to be deducible from this preliminary investigation.

I. HISTORICAL.

(1) General Considerations.

The occurrence of fracture in metallic parts owing to a succession of stresses, sometimes positive and sometimes negative, has for a very long time past been recognised. As far back as 1849 a British Royal Commission instituted for the investigation of the application of iron to railway construction, pointed out these types of stresses as possible causes of failure. Fairbairn reverted to this suggestion ten years later, and ultimately Braithwaite, at about the same period, attributed the breakage of some girders supporting a brewery vat to the fact that the vat was alternately filled and emptied. It was, however, Wöhler who first studied the phenomenon and stated its laws. The fracture of a metallic member may, he says,[1] be occasioned not only by the application of a stress exceeding the breaking load, but also by the repetition of a stress inferior to that load. If the maximum stress to which the part is subjected be indicated by F, and any stress comprised within 0 and F be indicated by f, the maximum stress that can be borne without fracture is in the neighbourhood of the elastic limit when the stress varies between 0 and $+F$; higher than the elastic limit (and the nearer to the breaking strain itself the larger f is) when the stress varies between f to F; and, finally, lower than the elastic limit when the stress[2] varies between $-F$ and $+F$.

Generally speaking, in repeated tensile and compressive stresses, the results obtained do not depend on the absolute value of each of these stresses but on the sum of their intensity, stated as an absolute value: a stress varying between $-F$ to $+F$ occasions the same fatigue as the variations of stresses comprised between 0 and 2F.

[1] *Zeitschrift für Bauwesen*, Berlin, 1866 and 1870, *passim*.

[2] Spangenberg, *Über das Verhalten der Metalle bei wiederholten Anstrengungen*, Berlin, 1875.

Bauschinger[1] threw a light upon what might appear to be somewhat abnormal in this statement by assuming that the ordinary elastic limit was artificially raised by various causes, such as strain hardening and others, and that alternating stresses restored this elastic limit to its normal value, comprised within the half and three-fifths of the other. The maximum stress which a metal can indefinitely withstand, when undergoing alternating deformations, will be exactly equal to this normal elastic limit which Bauschinger calls the "natural" elastic limit.

From the experiments of Wöhler and of Bauschinger, a certain number of formulas have been deduced giving the limit of danger, R, of alternating stresses calculated out per unit of surface.[2]

Launhardt's Formula.—$R_1 = E + (R - E)\frac{f}{F}$

when E = normal elastic limit and R = breaking load.

Weyrauch's Formula.—$R_1 = E - (E - e)\frac{f}{F}$

when e equals Bauschinger's "natural" elastic limit.

Seefehlner's Formula.—$R_1 = \frac{2}{3}\left(1 + \frac{f}{2F}\right)R$

a formula in which the stresses intervene with their own proper signs.

Rogers' Formula.[3]—$R_1 = 0{\cdot}4E + 0{\cdot}26R$.

Numerous experiments have since confirmed the tests carried out by Wöhler and by Bauschinger.

Sulzer,[4] on studying the cracking of boiler plates, arrives at the conclusion that the stresses to which a piece of metal is subjected suffice to lead to cracking when they exceed the elastic limit, no matter how high the tensile strength of the metal may be.

1 *Mitteilungen aus dem Mech. Techn.-Labor. in München*, 1886.

2 Weyrauch, *Stabilité des constructions en fer et en acier* (translated by Svilokossitch), Paris, 1888.

3 *Journal of the Iron and Steel Institute*, 1905, No. I. p. 487.

4 *Zeitschrift des Vereines Deutscher Ingenieure*, 1907, vol. li. p. 1165.

Dudley[1] had already noted that, in alternating bend tests carried out on axles by the Pennsylvania Railroad Company, breaking almost invariably occurred when the calculated maximum stress reached one-half the ordinary elastic limit. Stanton[2] and Bairstow verified Wöhler's law in alternating tensile and compression tests and found that the elastic limit, ascertained after the action of a certain number of alternating stresses, was lower than the original elastic limit.

Later, Bairstow,[3] in completing his earlier experiments, ascertained that after a certain number of cyclical variations in tension and compression in the vicinity of the elastic limit, iron and steel adapt themselves to these variations so as to remain perfectly elastic and to exhibit no trace of fatigue. This arises from the fact, as stated by Bauschinger, that the elastic limits under tension and compression are not immutable but may be lowered or raised by repeated stresses. This faculty of adaptation is limited; if it be exceeded, the test-piece loses its elasticity and goes on to fracture. In any case the variations of the elastic limit of tensile strength are slighter than those of the elastic limit of compressional strength, so that it is this latter which determines the permissible variation of stresses.

The same conclusions are arrived at by Howard[4] (rotary bends), by Smith[5] (alternating tension and compression), and by Turner[6] (rotary bends).

Different conclusions have, however, been enunciated during quite recent years. Eden,[7] Rose, and Cunningham claim to have been unable to find a stress-limit, that is to say, a limit of stress, however slight, for which the necessary number of alternations required to produce fracture becomes infinite.

Stromeyer,[8] going even further, has denied the existence of any relation between resistance to alternating stresses, elastic

[1] *Iron and Steel Metallurgist*, 1904, vol. vii. p. 134.

[2] *Institution of Civil Engineers*, 1906, vol. clxvi. p. 78.

[3] *Philosophical Transactions*, 1909, vol. ccx. Series A.

[4] Fifth Congress of the International Association for the Testing of Materials, Copenhagen, 1909, vol. i. Proceedings No. 5.

[5] *Proceedings of the Institution of Mechanical Engineers*, 1909, p. 1237.

[6] *Engineering*, 1911, vol. xcii. p. 305.

[7] *Proceedings of the Institution of Mechanical Engineers*, 1911, p. 839.

[8] *Ibid*, p. 884.

limit, and breaking strain, a proposition which has been taken up and made largely his own by Roos af Hjelmsäter.[1]

Much more recent, and far less numerous, have been repeated impact tests. Seaton and Jude[2] were the first to direct attention to them in connection with nuts of connecting rods, the breaking of which could not be explained by any considerations derived from ordinary tensile tests or even by the Wöhler test.

Arnold,[3] Stanton, and Bairstow,[4] and more recently Kommers, Bairstow, and Roos af Hjelmsäter have investigated this type of stresses. An opportunity of noting their conclusions will be afforded in the paragraphs which follow.

Vibrational tests are even newer. Although the injurious influence of vibrations was suspected long ago, de Freminville[5] was the first, so far as the author is aware, who distinctly recorded the fact and who endeavoured to furnish an explanation. "In metallic rods and bars," he states, "elementary vibrations are propagated with but a very slight loss in work and are reflected back again from the ends of these conductors. If these vibrations are set up by a number of successive emissions, the emanating vibrations encounter the reflected vibrations and considerable stresses result." Excessive stresses leading to breakages may be set up by waves, or considerable vibrations being arrested in their course in some point within the mass.[6] "These vibrations occasion, at this point, cracks, for the prevention of which any mode of strengthening the piece is absolutely useless."[7]

A little later, Henry,[8] investigating the propagation of pressures within elastic bodies, noted that "if there is complete synchronism between the vibratory movement a solid body may assume the periodic repetition of the stress, the vibratory movement becomes exceedingly exaggerated, and

[1] New York Congress of the International Association for the Testing of Materials, 1912, vol. ii. Part II., Section A.

[2] *Proceedings of the Institution of Mechanical Engineers*, 1904, p. 1135.

[3] *Iron and Steel Magazine*, 1904, vol. viii. p. 433.

[4] *Proceedings of the Institution of Mechanical Engineers*, 1908, p. 889.

[5] *Revue de Métallurgie*, 1906, vol. iii. p. 61. [6] *Ibid.*, 1907, vol. vi. p. 833.

[7] Frémont, *Bulletin de la Société d'Encouragement*, 1909, Part I., p. 653; and Faroux, *Vie Automobile*, July 23, 1910.

[8] *Revue de Métallurgie*, 1910, vol. viii. p. 1171.

develops elastic stresses wholly disproportionate to the intensity of the isolated stresses."

He succeeded in establishing that "for any simple cylindrical body subjected in the direction of its axis to a simple sinusoidal pulsation applied to one extremity, the other being fixed, periodicities exist at which the body will undergo fracture, independent of what the amplitude of the initial pulsation may have been." Boudouard,[1] repeating an experiment of A. Guillet,[2] investigated the influence of various factors on the resistance to vibrations of cylindrical bars vibrating in diapason. He arrived at the conclusion that fracture occurred on stresses far below the ordinary elastic limit.

(2) Influence of the Chemical Composition.

Railway engineers have long since noticed that hard metals resist the alternating bending stresses to which axles and rails are subjected far better than soft metals. This observation has been confirmed by a large number of experimenters, notably by Stanton and Bairstow[3] and by Howard.[4] The latter has pointed out the remarkable resistance of steels containing 0·75 to 0·80 per cent. of carbon to rotary bending stresses. The resistance diminishes both above and below that percentage. Seaton and Jude,[5] in experiments on repeated impact tests, found that, on the contrary, the resistance diminishes on passing from 0·15 to 0·30 per cent. of carbon. This conclusion is confirmed by Stanton and Bairstow,[6] but only in regard to impacts of a certain intensity. This is just the opposite of what would occur when very weak impacts are employed.

M'William and Barnes[7] came to the same conclusions as Seaton and Jude. Further, steel with 0·75 to 0·80 per cent.

[1] *Bulletin de la Société d'Encouragement pour l'Industrie Nationale*, 1910, Part II., p. 545.

[2] *Revue de Métallurgie*, 1909, vol. vi. p. 885.

[3] *Institution of Civil Engineers*, 1906, vol. clxvi. p. 78.

[4] Copenhagen Congress of the International Testing Association, 1909, vol. i. Proceedings No. 5.

[5] *Proceedings of the Institution of Mechanical Engineers*, 1904, p. 1135.

[6] *Ibid.*, 1908, p. 889.

[7] *Journal of the Iron and Steel Institute*, 1909, No. I. p. 348.

of carbon displays a relatively good resistance not only to rotary bending stresses, but also to repeated shock. Finally, Boudouard[1] notes that the number of vibrations necessary to fracture a bar varies in inverse proportion to the percentage of carbon.

Impurities, such as slag, manganese sulphide, &c., are described as injurious both for alternating bending or rotary stresses, and in the case of repeated impacts. In being the last to solidify, and by their contraction at the time of so doing, they leave minute fissures within the steel which become more pronounced on the repetition of stresses (Longdridge,[2] Dudley[3]).

Phosphorus and nitrogen have a favourable influence on the resistance to alternating bending stresses (Stromeyer,[4] Arnold,[5] Stead, and Kommers[6]), but not to repeated shocks.

The presence of nickel and of titanium considerably raises the resistance to alternating bending stresses (Stanton,[7] Smith,[8] and Lake[9]), but not to repeated shocks. Occluded hydrogen, on the other hand, is injurious in the case of repeated shocks (Longmuir[10]).

Lastly, if the source of origin of the steel be taken into account, Biard[11] shows that, taking as a basis the statistics of the German Railway Union as to the relative breakage of axles owing to the development of cracks, the steels assume the following order and relative values:—

	Value.
Open-hearth steel	1·0
Bessemer steel	1·6
Crucible steel	3·0
Puddled steel	3·9
Crystalline iron	4·7
Fibrous iron	10·9

[1] *Bulletin de la Société d'Encouragement*, 1910, Part II., p. 545.

[2] *Proceedings of the Institution of Mechanical Engineers*, 1908, p. 989.

[3] Sixth Congress of the International Association for the Testing of Materials, New York, 1912, vol. ii. Part II., Section A.

[4] *Proceedings of the Institution of Mechanical Engineers*, 1911, p. 884.

[5] *Ibid.*, p. 887.

[6] New York Congress of the International Testing Association, 1912, vol. ii. Part II., Section A.

[7] *Journal of the Iron and Steel Institute*, 1908, No. I. p. 54.

[8] *Proceedings of the Institution of Mechanical Engineers*, 1909, p. 1237.

[9] *Metallurgical and Chemical Engineering*, 1913, vol. xi. p. 144.

[10] *Journal of the Iron and Steel Institute*, 1911, No. I. p. 147.

[11] *Revue Générale des Chemins de Fer*, 1903.

Boudouard, on the other hand, claims that puddled iron has a much higher resistance to vibrations than dead-soft steel.

(3) Influence of Treatment.

Hardening seems to raise considerably the resistance to alternating stresses, and annealing to have just the opposite effect. This is at any rate the conclusion to which Rogers,[1] Stanton,[2] Blount, Kirkaldy and Riall-Sankey,[3] Eden, Rose and Cunningham (alternating bending stresses), Gardner [4] (rotary bending stresses), Smith (alternating tensile and compressive stresses), and Seaton and Jude (repeated shocks) have arrived.

Hardening, on the other hand, diminishes the resistance to repeated shock, according to M'William and Barnes. It likewise diminishes the resistance to vibrations in, at any rate, hard steels (Boudouard). Overheated steel has a very poor resistance to alternating bending stresses, which might be anticipated from the foregoing, but it is possible to restore the metal by appropriate treatment (Rogers, Richards and Stead [5]).

A sorbitic structure, obtained by hardening and annealing, is described by Richards and Stead,[6] and by Boudouard as ensuring the maximum resistance in the case of alternating bending stresses and vibrations. The opposite occurs in repeated impact tests, so far as soft steels are concerned, according to M'William and Barnes.

Lastly, according to Cunningham,[7] there is no treatment which improves resistance to alternating bending stresses, tension, or compression by raising the permissible load: the sole advantage of treatment is that it increases the number of alternations before fracture under a given load.

It should be remembered that, according to Stromeyer,[8] there is, in similar cases, no relation whatever between endurance, the elastic limit, and the resistance of a metal.

[1] *Journal of the Iron and Steel Institute*, 1905, No. I. p. 486.
[2] *Ibid.*, 1908, No. I. p. 54.
[3] *Proceedings of the Institution of Mechanical Engineers*, 1910, p. 715.
[4] *Journal of the Iron and Steel Institute*, 1905, No. I. p. 481.
[5] *Ibid.*, 1905, No. I. p. 84. [6] *Ibid.*, 1903, No. I. pp. 119 and 141.
[7] *Proceedings of the Institution of Mechanical Engineers*, 1911, p. 839. [8] *Ibid.*, p. 884.

A curious point recorded by Bairstow[1] is that a fatigued steel, that is to say, a steel the elastic limit of which has undergone displacement by the repetition of stresses, regains its ordinary limit after a rest of several months, or on treatment with boiling water, a phenomena which has been contradicted by Eden, Rose, and Cunningham.

(4) Influence of Shape of Test-pieces.

Stanton and Bairstow,[2] Eden, Rose and Cunningham (*op. cit.*), Stanton, and Kommers have, one after another, shown the disastrous influence of deep grooves and even of mere tool marks in alternating bend tests, and Freminville[3] and Frémont[4] have pointed out the reason, which is that deep grooves and tool marks stop the vibrations. It is evidently the same in the case of defective bearings; the injurious action of "play" in bearings is well known to all fitters.

According to Stanton and Bairstow the angle of the notch in repeated impact tests has no influence on the number of blows which occasion fracture, which depends solely on the relation between the diameter at the bottom of the notch, the diameter of the test-piece, and the distance between supports.

(5) Influence of the Rate of Repetition of the Stresses.

From tests carried out by Reynolds and Smith[5] (alternating bends), Bairstow[6] (alternating tension and compression), and Arnold[7] (repeated impacts), it results that the resistance of the metal seems to vary in inverse proportion to the rapidity of the reversal of the stresses. Hopkinson[8] and Roos af Hjelmsäter[9] have arrived at the opposite conclusion, the first

[1] *Philosophical Transactions*, 1909, vol. ccx. Series A.
[2] *Institution of Civil Engineers*, 1906, vol. clxvi. p. 78.
[3] *Revue de Métallurgie*, 1907, vol. vi. p. 833.
[4] *Société d'Encouragement pour l'Industrie Nationale*, 1909, Part I., p. 653.
[5] *Philosophical Transactions*, 1902. [6] *Ibid.*, 1909.
[7] *Iron and Steel Magazine*, 1904, vol. viii. p. 433.
[8] *Proceedings of the Royal Society*, Series A., vol. lxxxvi. p. 131.
[9] International Testing Association, New York, 1912, vol. ii. Part II., Section A.

named in periodic tensile tests, and the second in rotary bending tests. Finally, Stanton [1] and Eden, Rose and Cunningham conclude, from alternating bending tests, that there is no relation between rate of speed and endurance, so far, that is, as rates of speed not exceeding 2000 alternations per minute are concerned.

(6) Mode of Fracture.

Whatever be the method by which fracture is produced (tension, bending, or shock), every author agrees in saying that it takes place gradually by the development of a flaw, which, to begin with, may be only microscopic. According to Seaton and Jude, Rogers,[2] Stanton and Bairstow, and Giessen,[3] the flaw develops, by preference, within the ferrite. This development takes place either by slip-bands or by twinnings (Ewing and Humfrey,[4] Seaton and Jude, and Stanton and Bairstow).

Longdridge [5] and Ziegler [6] attribute the fracture to the presence of slags or of impurities such as manganese sulphide, which are the seat of microscopic flaws which gradually enlarge under stress.

(7) Relation between Alternating Stress Tests and Simple Impact Tests.

From certain tests carried out by Stanton, it results that the resistance to repeated impacts agrees with the resistance to simple impact, when the number of impacts determining fracture is low. The relations are however reversed when the number of shocks is considerable. Roos af Hjelmsäter has obtained concordant results between endurance and rotary bending tests and repeated impact tests, but he considers that, generally speaking, endurance under alternating tests is the

[1] *Institution of Civil Engineers*, 1906, vol. cxlvi. p. 78.

[2] *Journal of the Iron and Steel Institute*, 1905, No. I. p. 484.

[3] *Journal of the Iron and Steel Institute: Carnegie Scholarship Memoirs*, 1909, vol. i. p. 1.

[4] *Philosophical Transactions*, 1902.

[5] *Proceedings of the Institution of Mechanical Engineers*, 1908, p. 989.

[6] *Revue de Métallurgie*, 1911, vol. viii. p. 655.

reverse to endurance under simple impact. Dudley, on the other hand, remarked that rails possessed of a low degree of ductility showed themselves incapable of withstanding, particularly at low temperatures, the rapidly alternating stresses corresponding to the strong bending moments imposed in actual service conditions. In contradistinction to Roos af Hjelmsäter, Bairstow [1] believes in the complete lack of agreement between the results of repeated shock tests and the Wöhler test.

II. DESCRIPTION OF APPARATUS AND OF THE MATERIALS INVESTIGATED.

(1) Repeated Impact Tests.

The machine employed for the author's repeated impact tests is the same as that employed by Stanton and Bairstow, constructed by the Cambridge Scientific Instrument Company. Fig. 1 shows the arrangement for raising the hammer. To the end of the driving shaft of the pulley A is connected a handle

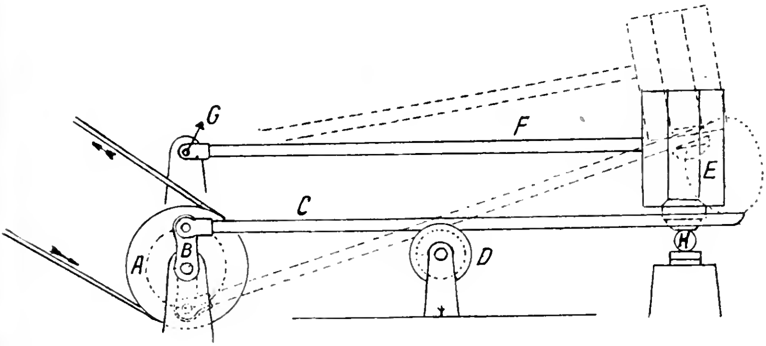


Fig. 1.

B, itself connected to the bar C. This bar is supported at any variable point in its length by a roller D, so that the circular movement imparted to the end fastened to the handle compels it to roll and slide on the roller. Its further extremity therefore describes an oval trajectory, represented in the figure by

[1] *Proceedings of the Institution of Mechanical Engineers*, 1911, p. 919.

dotted lines. This end being bent at a right angle, the bar C engages during a portion of its course with the underside of the drop-weight E and raises it. E is fixed to a rod F, which moves about the point G. When it has attained its highest point the bar C advances forwards, disengages itself from the drop-weight, and lets the latter fall freely on the test-piece H. The height from which the drop-weight E falls can be varied by moving the roller D.

The test-piece rests on two supports distant 114 millimetres from one another. The drop-weight strikes at an equal distance between the supports. At each blow the test-piece turns through an angle of 180° by means of the mechanism shown in Fig. 2. The toothed wheel J turns

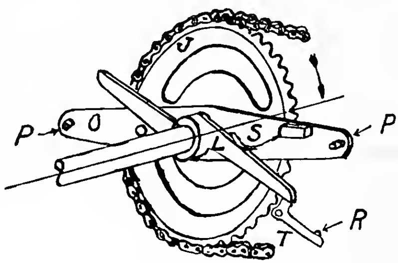


FIG. 2.

uniformly and makes a revolution with every second blow of the drop-weight. This wheel is connected, by means of a spring S, with the mandril which holds the test-piece. During the fall of the weight the spring is compressed and the test-piece cannot rotate because the lever L is kept in place by the stop T. When, however, the blow is delivered the rigid arm O of the wheel J liberates L, thanks to one of the cottar-pins P which come in contact with the back R of the stop T. When the test-piece breaks, the drop-weight, continuing its course, strikes against a hand-wheel and cuts off the current driving the motor which drives the pulley A. A revolution-counter registers the number of revolutions this pulley has made and therefore the number of blows the test-piece has withstood.

In the author's experiments the number of blows was from

80 to 140 per minute, and the height of fall of the drop-weight E from half an inch to an inch (12·7 to 25·4 millimetres).

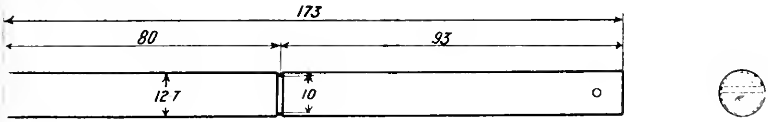


FIG. 3.

Fig. 3 shows the dimensions of the test-piece. It will be seen that this test-piece is furnished with a notch which was always made by the same tool, which was specially reserved for this purpose.

(2) ENDURANCE TESTS.

The arrangement employed by the author does not differ appreciably from that which was used by Wöhler for the

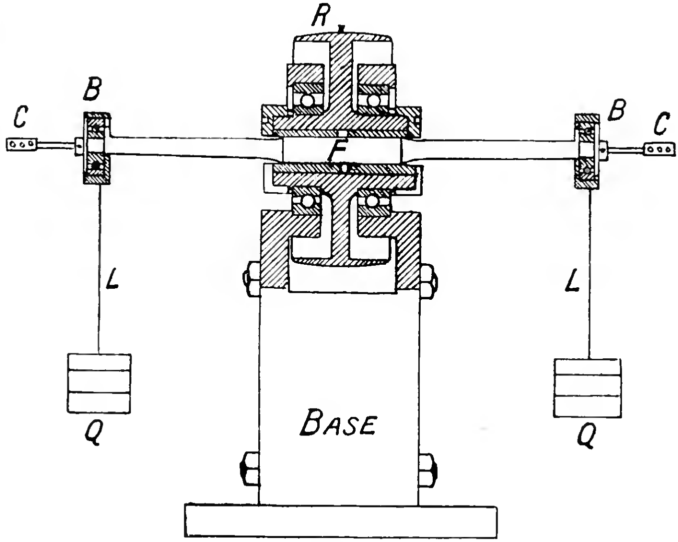


FIG. 4.

rotary bend test. It consists of a carefully turned pulley R (Fig. 4) resting on ball-bearings. The test-piece F is clutched in this pulley by means of a conical chuck. The load Q is

suspended from the extremity of the test-piece by means of the rods L and the bearings B, mounted upon balls. C are the revolution-counters, the machine being generally geared at a rate of 1000 revolutions per minute.

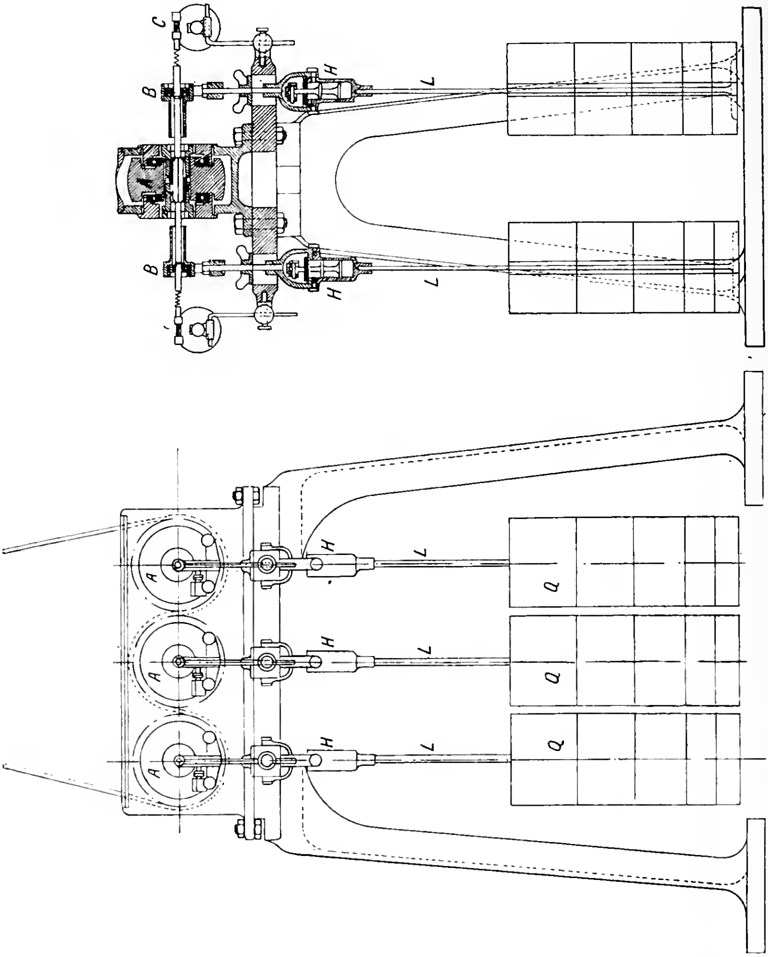


Fig. 5.

In order to accelerate the experiments, the author ultimately constructed a machine of the same kind allowing of three test-pieces being tested at a time. This machine is shown in Fig. 5.

It only differs from the preceding by the provision of three pulleys driven by the same belt at a speed of 1000 revolutions per minute, and by the addition of oil cushions intended to deaden vibrations. These oil cushions form part of an arrangement such that the load Q is connected with the test-piece by a suspended ball-and-socket arrangement. It is

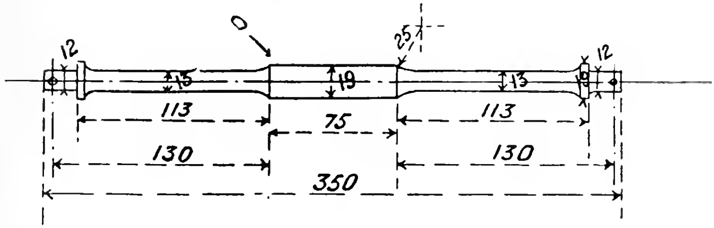


FIG. 6.

possible to interpolate or suppress the oil cushions between the load Q and the test-piece, at will.

Fig. 6 shows the principal dimensions of the test-piece. The maximum tensions only prevail, it is obvious, within the dangerous section, that is to say, at the groove O. The test-pieces have been carefully polished at this region so as to remove all trace of machining and to avoid every trace of flaw.

(3) VIBRATION TESTS.

A. Guillet,[1] who was the first to have occasion to note the fracture of metallic parts (octave couplers) by vibration, has described a highly delicate arrangement for ensuring the direct maintenance of vibrations at constant amplitude. The iron rod to be investigated is fixed by one of its extremities to a sort of socket rising perpendicularly from a heavy base provided with two longitudinal grooves along which can lie, respectively, an electro-magnet intended to connect with the rod and the connecting switch which governs the latter. This contact is formed by a very fine metallic wire under high tension (movable terminal of the contact) and tightly fastened in relation to the vibrating rod, to which it is fastened by a

[1] *Revue de Métallurgie*, 1909, vol. vi. p. 885; and *Comptes Rendus*, 27th September 1909.

supple fastening (sewing cotton). A small metal or carbon cylinder (fixed terminal of contact) can be adjusted micrometrically, in the vicinity of the movable terminal. The contact between the rod and the movable terminal parallel to it is regulated by the displacement of the whole body of contact perpendicularly to the direction of the rod.

Boudouard[1] has employed practically the same arrangement. He replaces the metallic wire which constitutes the movable terminal, by the blade of a vertical spring fastened by a thread to the vibrating rod. The fixation of the rod at its fixed end is effected by means of a little hand rolling-mill, the rolls of which have been replaced by two hard steel jaws, accurately adjusted and forming the holder for the bar to be examined.

After several experiments it was found necessary to discard these two arrangements, as far too delicate in the conditions under which the work was being carried out. It was necessary to devise an apparatus the adjustment of which would not be disturbed either by disturbances arising from the proximity of the works or by those occasioned by the different apparatus placed in the vicinity, such as Frémont dropweights, &c. The apparatus had likewise to be such that, in the author's absence, a workman could put it into operation, and that its amplitude should be easily adjusted and maintained absolutely constant during the entire period of the experiment. After many attempts the following arrangement, which gave perfect satisfaction, was arrived at:—

The rod to be investigated (Fig. 7) is fixed to the head of a weight of about 2000 kilogrammes by means of a conical socket of which Fig. 8 gives the details. By taking care to let the test-piece rest on the points A and B only (Fig. 7; it is only required to turn up the portion A, B—some hundredths short) an exceedingly effective grip is assured, which renders the test-piece absolutely rigid with the weight.

The arrangement for keeping up the vibratory movement is constituted by two electro-magnets symmetrically arranged and to which current is furnished alternatingly by a distributor C (Fig. 9). The current employed is a continuous one

[1] *Bulletin de la Société d'Encouragement*, 1910, Part II., p. 545.

at 220 volts. After having traversed the incandescent lamps which constitute the resistances the current reaches the

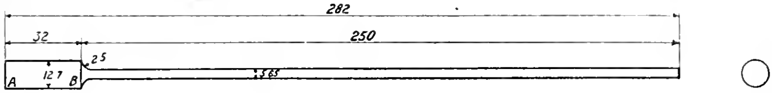


FIG. 7.

distributor, which consists of three copper rings, or, rather, of one ring and two half-rings mounted outside an ebonite ring

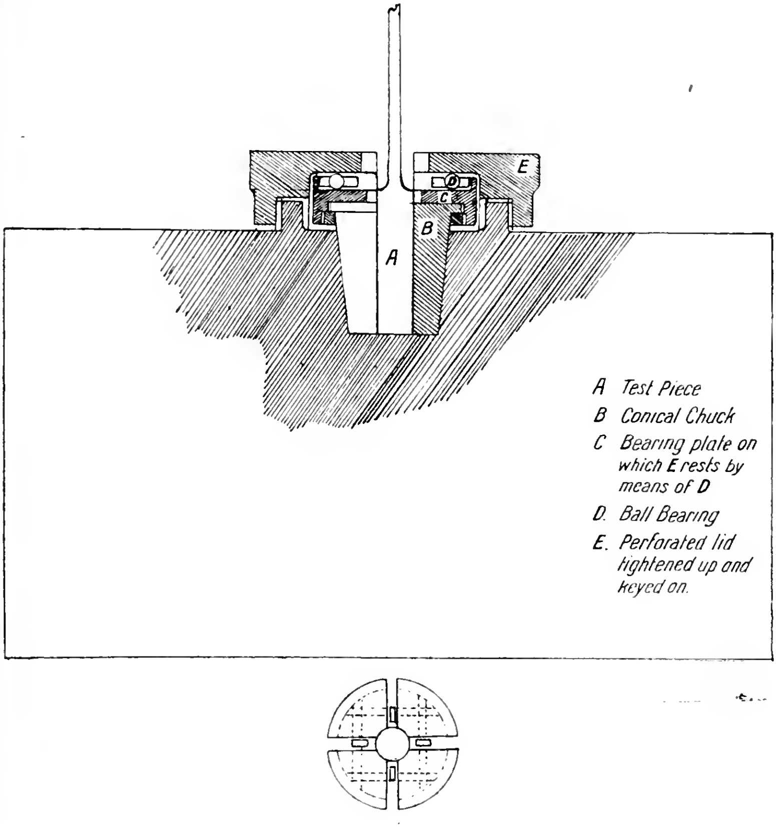


FIG. 8.

in such a way that the two half-rings are opposite one another. Three brushes conduct the current to the rings.

The distributor is given a motion of continuous rotation (1800 revolutions per minute) by means of a little electric motor M. Two disc condensers of a microfarad capacity each, coupled in series D, prevent all sparking and wear of the contacts. A revolution-counter, not shown on the plan, is geared up with

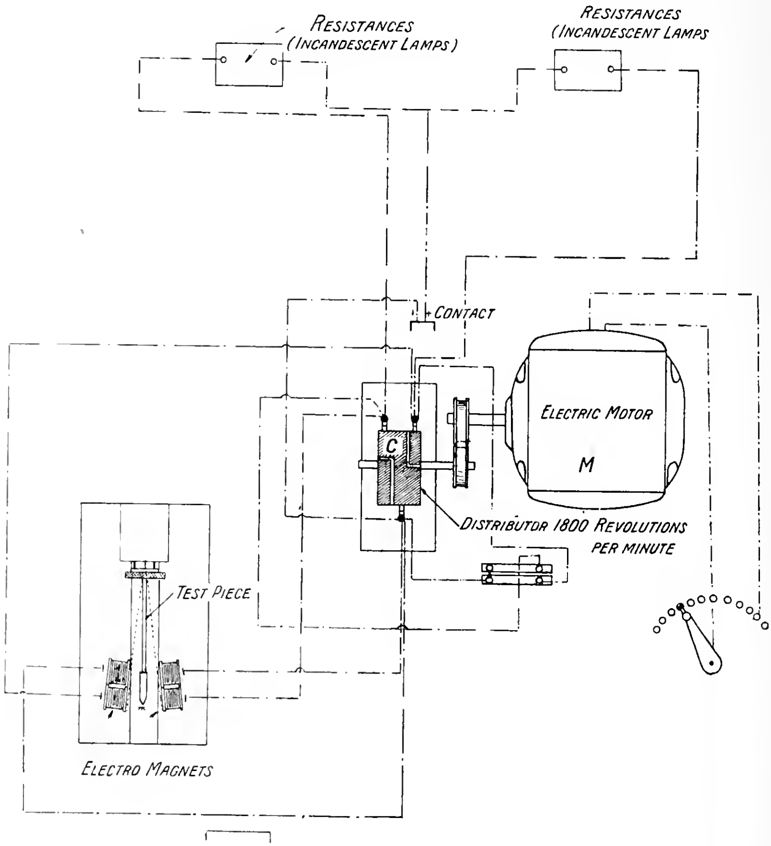


FIG. 9.

the distributor C. Once the electric motor M has been set at its normal rate of speed, the test-piece is driven, so to speak, mechanically and undergoes as many complete vibrations as the distributor makes revolutions. This motion is absolutely constant and only ceases when the test-piece undergoes fracture.

The electro-magnets, of horse-shoe shape, are formed of 36 layers of 53 turns of 1-millimetre cotton-covered wire. The diameter of the cores is 18 millimetres. Each magnet is mounted on a support capable of parallel displacement with the test-piece. The magnets can further move in two other directions: (1) towards, or away from the test-piece, by sliding along their supports, and (2) they are pivoted in a horizontal plane so that they can remain practically parallel with the test-piece once the latter has been put into motion. Wedges or screws serve for tightening up the magnets and their supports, once they are in position.

A metallic mass m surmounts the movable end of the test-piece. This arrangement considerably reduces the energy consumption and enables amplitudes of 60 millimetres to be attained with 1·5 ampere. The mass m has an oblong shape 80 millimetres in length, 7 millimetres in width, and 20 millimetres in depth. A leaf of tinfoil placed on each side of this mass prevents the test-piece from sticking to the magnets.

The shape and dimensions of the test-piece have already been given in Fig. 7. The notch was carefully polished so as to remove every trace of the tool and to avoid every trace of flaw.

(4) Simple Impact Tests.

The shock test was always carried out by means of the Frémont drop-weight.

The test-pieces used were of the shape recommended by Frémont: 8×10 millimetres section and a length of 35 millimetres. Except where otherwise stated, all the shock test-pieces which were dealt with had been notched with a saw-cut 1 millimetre in width and 1 millimetre in depth. The resiliences have always been expressed in kilogrammetres per square centimetre of effective section.

(5) Chemical Composition of the Steel Test-piecfs.

Table I. gives the chemical composition of the steels employed in the author's experiments.

TABLE I.

Steel.	C per cent.	Mn per cent.	Si per cent.	S per cent.	P per cent.	Cr per cent.	Ni per cent.	Description of Steel.
A	...	...	...	...	...	...	...	Swedish iron
B	0·07	0·60	0·02	0·03	0·02	...	...	Open-hearth
C	0·27	1·30	0·30	0·02	0·03	...	...	Open-hearth
D	0·46	1	0·20	0·02	0·04	...	...	Open-hearth
E	0·25	0·30	0·03	0·02	0·02	...	0·30	Electric
F	0·11	0·43	0·03	0·01	0·01	...	1·98	Open-hearth
G	0·40	...	...	...	...	...	24·87	Crucible
H	0·09	0·35	0·20	0·01	0·01	1·20	4·76	Crucible
I	0·23	0·40	0·18	0·02	0·02	1·66	3·18	Electric
K	0·30	0·48	0·22	0·01	0·01	1·43	4·55	Crucible
P	0·17	0·40	0·03	0·02	0·02	...	...	Open-hearth
Q	0·40	0·83	0·10	0·02	0·05	...	...	Open-hearth

(6) TREATMENT.

With the exception of the Swedish iron A and the 25 per cent. nickel steel, all the steels were, to begin with, forged in round bars 20 millimetres in diameter. The treatment was always carried out on bars cut to the requisite length, and not on the finished test-pieces, except for steels C, D, E, H, I, K, and P, whenever they had to be tested in the hardened state. Below are given the details of the various treatments. For the sake of simplicity, each treatment has been designated by a letter.

RL, *as rolled* (untreated).

R, normalised (annealed). The bar is kept for fifteen to twenty minutes :—

	Temperature °C.
For iron A	at 925°
For steels B, E, F, H, P	at 900°
,, C, D, G, I, Q	at 850°

It is then air-cooled (except steel D, which was cooled in a box, out of contact with air).

TR (TRH, TRO), *quenched and annealed.* The bar is quenched

			From
In water,	for steels	B, E, F, P	900°
,,	,,	C	850°
In oil	,,	D, H, I, Q	850°
In air	,,	K	800°

and then annealed for about :—

B and E	2 hours at 625° to 650°
C (treatment TRO) and P . .	1 hour at 625° to 650°
D (treatment TRO), F, and Q .	$1\frac{1}{2}$ hours at 600° to 625°
I	1 hour at 600° to 625°
H and K	4 hours at 600° to 625°

The two latter steels were also cooled out of contact with air.

The TRH treatments of steels C and D are treatments similar to TRO, but designed to give these steels a high resilience.

T, *quenched;* the bar is quenched at

925° in water, for the Swedish iron A.
900° ,, ,, steels B, E, F, and H.
850° ,, ,, steel G.
850° in tepid water (50° to 60°) for steel C.
850° in oil for steels D and I.
800° in air for steel K.

B, *overheated.* From all these steels fire bars were made, 25×25 millimetres square and about 50 centimetres long. These bars were placed, for one month, in the hearths of coke furnaces intended for the hardening of automobile parts. At the end of that period they were withdrawn, and from those which appeared most spoiled test-pieces were made. Steel K had, naturally, to undergo annealing after superheating in order to be workable by the tool, but the test-pieces KB were air-hardened after machining.

III. DETAILS OF THE EXPERIMENTS.

(1) Repeated Impacts.

Table II. gives the details of the repeated impact tests carried out on the metals A, B, C, D, E, F, G, H, I, and K. All these metals were tested under four conditions: normalised (R); hardened and annealed (TR); hardened (T); and overheated (B). Exception must be made in the case of the wrought iron (A) and the steel containing 25 per cent. of nickel (G) which were not tested in the hardened and annealed condition, and the chromium-nickel steel (K) which was not

tested in the normalised condition. These treatments reveal nothing of any interest in the case of the steels referred to.

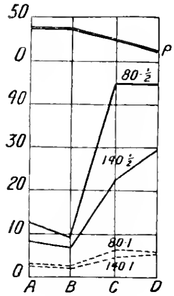


FIG. 10.
Normalised.

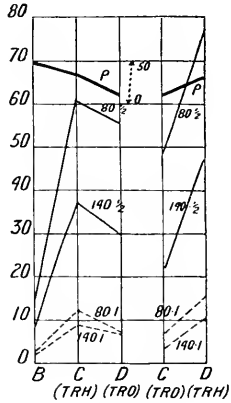


FIG. 11.
Quenched and Tempered.

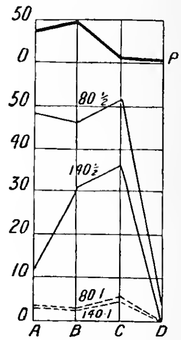


FIG. 12.
Tempered.

Steel G was tested in the condition in which it is ordinarily employed, that is to say, as rolled, instead of being normalised. Lastly, steels C and D were hardened and annealed in two different ways (TRH) and (TRO), the first of which conferred upon them a far higher degree of resilience than the second, without affecting the elastic limit, or the breaking strain.

Three tests were carried out for each steel and for each treatment. The means of these three tests have served for plotting the diagrams 10 to 21. After fracture a Frémont shock test-piece was taken from each repeated shock test-piece. The figures obtained from these test-pieces have been recorded in Table II., and the averages have served for the plotting of the curves ρ in diagrams 10 to 21. When the

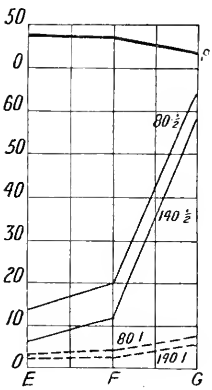


FIG. 13.
Normalised.

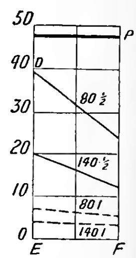


FIG. 14.
Quenched and Tempered.

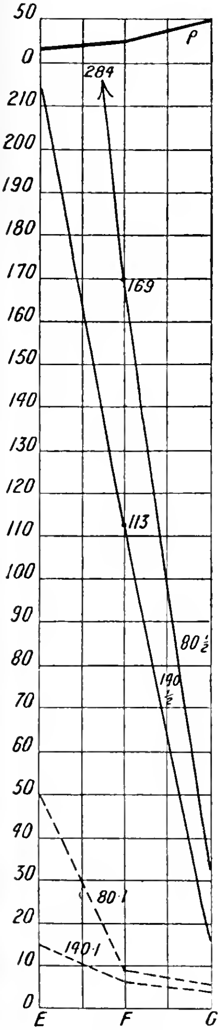


Fig. 15.
Quenched.

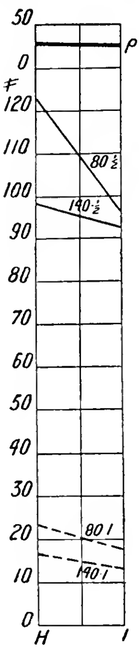


Fig. 16.
Normalised.

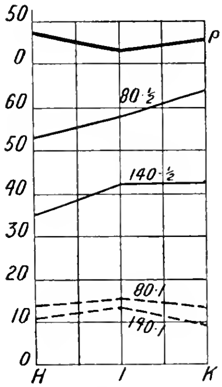


Fig. 17.
Quenched and Tempered.

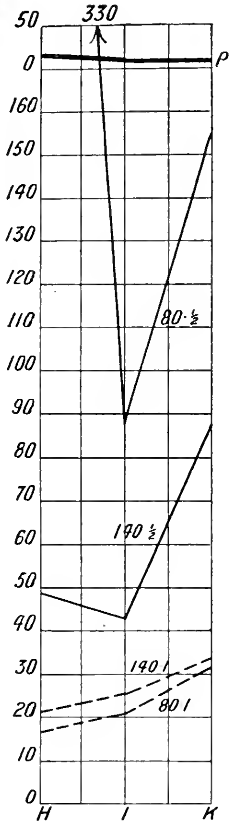


Fig. 18.
Quenched.

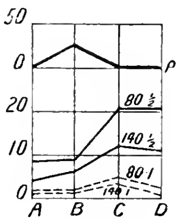


Fig. 19.
Overheated.

In Figs. 10 to 19 the ordinates represent the resistance to repeated shocks measured per 1000 blows, and the curves ρ give the resistance in kilogrammetres per square centimetre (scale 0 to 50). The letters relate to the descriptions of steel enumerated in Table I., p. 114.

test-piece for the repeated shock tests required to be hardened the Frémont shock test was prepared separately, but from the same piece of metal, and the two test-pieces hardened together.

(*a*) *Influence of the Depth of Fall and of the Rate of the Repetition of the Stress.*

The first conclusion to be drawn from an examination of the diagrams is that the resistance varies always in inverse ratio to the depth of fall and the rate of the repetition of the stress. Only one exception to this is afforded by the hardened nickel-chromium steels (Fig. 18). The two curves, however, coincide so closely that mere experimental error might have made one of them pass above or below the other. It should, indeed, be noted that the influence of the rate tends to become weaker and weaker in proportion as the depth of fall increases so that, provided the shock be sufficiently intense, the number of blows required to break the test-piece remains practically the same, no matter what the rate of the repetition of the stress may be. (See Figs. 10 to 13.)

(*b*) *Influence of Chemical Composition.*

In carbon steels the resistance varies directly with the percentage of carbon as long as this percentage does not exceed 0·25 to 0·30, but above this percentage the resistance has a tendency to diminish, and this tendency is increased by hardening[1] (Figs. 10, 11, and 12).

In other words, the semi-hard steels always display greater resistance than the mild steels. Hard steels resist better than mild steels (except in the hardened state), but not as well as the semi-hard steels. Swedish iron does not apparently display any greater resistance than soft steel.

Generally speaking, the nickel steels display greater resistance than soft carbon steels, but do not appear to be superior

[1] It should here be pointed out that the steel containing 0·25 per cent. of carbon contains likewise high percentages of manganese and of silicon. It is possible that these elements may exert some influence.

in this respect to semi-hard steels. This is only true in cases where the depth of fall is not excessive; when the shock attains a certain intensity the influence of the nickel disappears and the steel tends to behave like a simple carbon steel, no matter what the percentage of nickel may be. A second exception arises in the case of the steels containing from 0·30 to 2 per cent. of nickel, which in the hardened state display absolutely extraordinary resistances, far higher than those of the best carbon steel. The steel with 0·30 per cent. of nickel behaves almost as well or even better than steels containing higher nickel (with the exception of the steel with 25 per cent. of nickel, as rolled—Fig. 13). There is therefore no interest attaching to an increase in the percentage of nickel.[1]

Finally, the nickel-chromium steels display much greater resistance than ordinary carbon steels, or even than nickel steels. But, of the nickel chromium steels, the dead-soft steel is the most resistant, and the semi-hard steel the steel which gives the least satisfactory results (Figs. 16, 17, and 18).

It has been said that, generally speaking, the resistance varies in inverse ratio to the depth of fall. Nickel steels, and in particular those containing both nickel and chromium, are much more sensitive than carbon steels to any variation in the depth of fall. This sensitiveness reveals itself by a considerable increase in the resistance once the depth of fall decreases (Figs. 16 and 18).

(c) *Influence of Treatment.*

Hardening followed by annealing slightly increases the resistance of carbon steels. Its influence is, however, more appreciable on steels containing less than 0·30 per cent. of carbon than on "hardening steels." Thus, semi-hard steels, hardened and annealed, are always higher in resistance than hard steels that have undergone similar treatment. Owing to the same phenomenon, hardening followed by annealing

[1] It should however be pointed out that the steel containing 0·30 per cent. of nickel contains likewise 0·25 per cent. of carbon, whereas the 2 per cent. nickel steel only contains 0·11 per cent of carbon.

markedly raises the resistance of steels containing a low percentage of nickel (0·30 per cent. of nickel), but leaves steels with 2 per cent. of nickel practically unchanged. Lastly, it diminishes the resistance of nickel-chromium steels, but seems to have more influence upon soft nickel-chromium steels than on semi-hard steels. The latter, once hardened and annealed, display rather more resistance than the former when similarly treated. This is the reverse of what is found in the annealed (normalised) state.

Hardening (not followed by annealing) considerably raises the resistance of Swedish iron, and, particularly, of mild steel, at least when the depth of fall is not excessive. In the opposite case (and this is a general observation applicable to all steels independently of their composition) the influence of the depth of fall becomes paramount and obliterates every other influence, that of the rate of repetition of the stress, of the chemical composition and of the thermal treatment alike. Quenching either fails to affect or tends to diminish the resistance of semi-hard steel; it reduces to 0 that of the "hardening" steels. The presence of nickel, either alone or combined with chromium, exaggerates to an extraordinary degree the effect of the quenching. The resistance of steel with 0·30 per cent. of nickel which has been quenched is, as a regular thing, equal, in the author's experiments, to more than 25 times that of the same steel annealed, that is, for low depths of fall. That of steel containing 28 per cent. of nickel and quenched is, similarly, equal to nearly ten times that of the same steel after annealing; on the other hand, the steel with 25 per cent. of nickel subjected to the operation of quenching undergoes a sudden diminution in its resistance (nearly one-half). The nickel-chromium steels also have their resistance raised to a notable degree, but it is in the soft steels that the phenomenon is most marked, and in the semi-hard steels in which it is the least so.

Lastly, overheating notably diminishes the resistance of all steels. If there be certain exceptions (steels B, E, F and H) they may be explained by the considerations which will be dealt with in the succeeding paragraph.

(*d*) *Influence of the Brittleness of the Metal on the Resistance to Repeated Shocks.*

If diagrams 10 to 21 be examined, and the curves of resilience therein shown be compared with those of the resistance to repeated shocks, it will appear at first sight as if there was no relationship between the two types of test. As a matter of fact, if in carbon steels the resilience certainly diminishes simultaneously with the resistance to repeated impact, yet when we pass from semi-hard to hard steels (Figs. 10 and 11) it does not increase, but, on the contrary, diminishes when we pass from mild steels to semi-hard steels; this is just the opposite to what happens as regards resistance to repeated shocks. In the nickel steels the resilience remains practically constant when we pass from the steel with 0·3 per cent. of nickel to the steel with 25 per cent. of nickel, whereas the resistance to shock increases (Fig. 13) or diminishes (Fig. 14). The same remark holds good for the nickel-chromium steels (Figs. 16 and 18). On the other hand, the resilience and the resistance of the quenched hard carbon steels to repeated impact are lower than those of the same steels annealed; the resilience of mild steels after quenching is practically the same as that of mild steels after annealing, whereas their resistance to repeated shock is distinctly higher. On the contrary, the resilience of quenched semi-hard steels is well below that of the same steels annealed, whereas their resistance to repeated shock is slightly higher. The same remarks apply to the special steels, and in particular to the nickel-chromium steels. We should, doubtless, be led to conclude that there is a total absence of any co-relation between the brittleness test and the repeated shock test.

Such an opinion would, nevertheless, be an erroneous one. The steels that should be taken for comparison are not, as a matter of fact, two steels of distinctly different chemical composition, such as a semi-hard steel and a hard steel, or again, even two steels in two different physical states, such as a hard quenched steel and a hard annealed steel, and still less so two different steels in two different physical states, such as an annealed mild steel and a quenched nickel-chromium steel.

Too many factors intervene and differentiate conditions the variation of which may mask the relationships, whatever they may be, between the brittleness and the resistance to repeated shock. It is a good logical rule to compare only those objects which differ in not more than two properties at most, and the variations of which can be observed. What must be compared to enable us to draw a valid conclusion are two samples of the same steel in the same physical state (that is to say, possessing the same essential constituents) and differing from one another only in their resistance to simple shock, whose behaviour to repeated shock can be ascertained and noted. Fig. 11 offers an instance of this description. Here there are two samples of the same steel (the semi-hard steel C), both quenched and annealed, but of such a nature that one steel is relatively brittle (10 kilogrammetres), while the other possesses a far higher resilience (36 kilogrammetres). The number of blows required to effect fracture by repeated impact in the two cases respectively was—

	$\rho=35.$	$\rho=10.$
80–$\frac{1}{2}$	61,000	49,000
80–1	12,000	7,500
140–$\frac{1}{2}$	36,000	21,000
140–1	8,900	4,800

The following table gives the same particulars in regard to the hard steel D (Fig. 11):—

	$\rho=30.$	$\rho=10.$
80–$\frac{1}{2}$	75,000	56,000
80–1	16,000	7,000
140–$\frac{1}{2}$	47,000	30,000
140–1	10,000	7,000

If, on the other hand, the overheated steels be compared with the corresponding normalised steels, the following round figures are obtained (Figs. 19, 20, 21):—

Carbon Steels normalised (R) and overheated (B).

	A		B		C		D	
	R	B	R	B	R	B	R	B
$\rho=$	40	0	40	30	25	0	15	0
80–$\frac{1}{2}$ . .	12,600	8,300	9,400	9,100	44,700	20,800	44,300	20,500
80–1 . .	3,100	1,400	2,400	1,600	6,600	4,100	6,200	2,400
140–$\frac{1}{2}$ . .	8,000	3,800	7,200	5,800	22,900	12,500	29,100	11,400
140–1 . .	2,400	1,000	2,200	2,000	5,100	3,700	5,900	1,200

Nickel Steels normalised (R) and overheated (B).

	E		F		G	
	R	B	R	B	R	B
$\rho =$	40	15	35	15	20	0
80–½	14,200	9,600	19,400	12,100	64,400	6,700
80–1	3,300	2,300	3,900	3,300	7,600	2,300
140–½	6,500	5,100	12,100	7,300	58,800	3,800
140–1	2,200	2,500	2,600	2,000	5,500	800

Nickel-chromium Steels normalised (with the exception of K) and overheated.

	H		I		K	
	R	B	R	B	Air-hardened.	
$\rho =$	30	15	25	0	10	0
80–½	123,000	126,000	96,000	51,000	156,000	110,000
80–1	23,600	20,600	18,500	3,800	31,700	31,000
140–½	99,800	30,000	92,600	20,000	87,900	65,900
140–1	16,700	13,100	13,500	2,800	33,700	20,000

This comparison is suggestive enough! Every time the same steel in the same physical state (possessing the same essential constituents) undergoes—for any reason—a diminution of resilience, its resistance to repeated impact diminishes likewise, and, on the other hand, whenever (under the same conditions) the resilience remains sensibly constant, the resistance to repeated impact does not vary. Steel B furnishes a striking instance of the second portion of the foregoing proposition. If the state of the overheating of a steel can be defined by the abnormal brittleness which a steel acquires on prolonged heating (the only definition which possesses any practical interest), it is certain that steel B has not been actually overheated.[1] And it resists repeated impact equally well as in the annealed state.

It should be noted as a corollary to the foregoing proposition that the differences between the resistances of a normalised steel and a more or less overheated steel are greater in proportion as the depth of fall is less (steels E, F, and H).

[1] The prolonged heating of a mild steel with the object of rendering it brittle does not, by a long way, always lead to the desired result. This embodies an observation the author has often had occasion to make without being able to ascertain definitely the conditions under which the heating should be carried out in order to make a mild steel brittle.

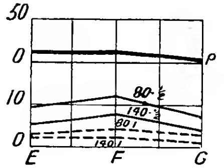


FIG. 20.
Overheated.

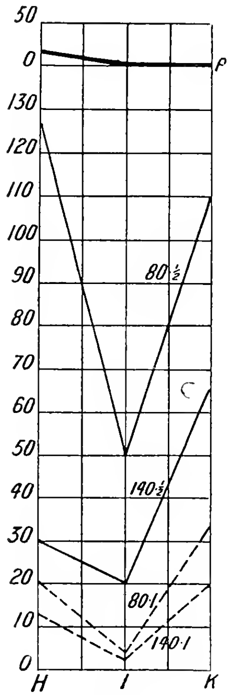


FIG. 21.
Overheated.

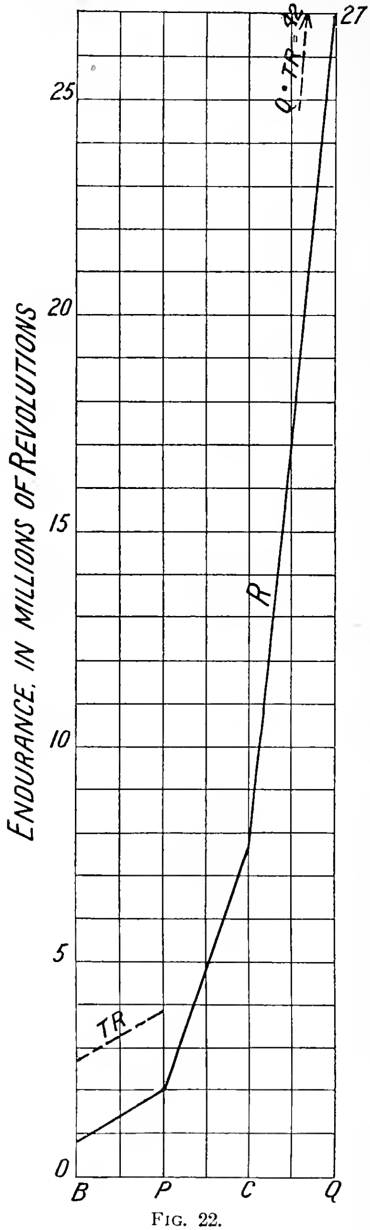


FIG. 22.

In Figs. 20 to 21 the ordinates represent the resistance to repeated shocks measured per 1000 blows, and the curves ρ give the resistance in kilogrammetres per sq. cm. (scale 0 to 50). For explanation of the lettering see inscription below Figs. 10–19, page 117.

Here is found once again the influence of the depth of fall which, as we know, tends to mask every other factor.

(*e*) *Mechanism of Rupture and Influence of the Texture on the Resistance to Repeated Shock.*

Figs. 30 to 34 represent, on natural scale, the fracture of test-pieces by repeated shock. These fractures are always similar and altogether characteristic. Fracture takes place by progressive fissuration. There exists at each point of fracture a dull zone occasioned by the fact that the edges of the crack have become roughened or dulled by rubbing against one another and the crack has enlarged until the moment when, the section having become too small, the test-piece has broken suddenly, yielding this time a crystalline fracture. This crystalline fracture invariably consists of a central band more or less wide and perpendicular to the line which joins the points of impact.

If we reflect upon the increase in the resistance which quenching confers on mild steels and the diminution in the resistance which it occasions in hard steels; if we note the remarkable resistance of the 25 per cent. nickel steel, as rolled as well as that of the quenched 0·30 and 2 per cent. nickel steels; if we observe, on the other hand, the reduction in the resistance caused by quenching the 25 per cent. nickel steel, and if we apply these same remarks to the nickel-chromium steels, we may conclude that austenite is the particular constituent which offers the most resistance to repeated shocks, that ferrite offers a far lower degree of resistance, and, finally, that of all the constituents martensite is the one whose resistance is lowest and, generally speaking, very closely in the vicinity of zero.

TABLE II.

I.—*Rate: 80 blows per minute. Fall: ½ inch (12·7 millimetres).*

Steel.	Treatment.	Number of Blows.	Average.	Resilience.
A	R	14,191 10,143 13,522	12,618	35 40 38
A	T	46,258 37,483 62,640	48,794	36 34 37
A	B	7,755 9,100 8,245	8,366	0 2 5
B	R	9,456 8,863 10,089	9,469	34 47 40
B	TR	12,537 15,234 16,652	14,807	57 43 52
B	T	45,997 48,198 47,123	47,087	57 55 52
B	B	8,360 9,704 9,394	9,152	35 28 32
C	R	39,912 47,363 47,080	44,785	30 27 32
C	TRH	56,030 62,617 64,840	61,163	30 40 37
C	TRO	51,098 44,520 51,272	48,960	12 7 9
C	T	59,818 51,524 43,258	51,533	5 0 3

TABLE II. (*Continued*).

Steel.	Treatment.	Number of Blows.	Average.	Resilience.
C	B	24,990 21,540 16,119	20,883	0 0 0
D	R	40,717 37,826 54,597	44,380	12 8 10
D	TRH	76,646 79,268 71,114	75,676	35 30 32
D	TRO	52,343 61,609 55,582	56,511	14 17 14
D	T	4,383 4,934 3,165	4,160	0 0 0
D	B	14,443 24,240 23,027	20,570	0 0 0
E	R	14,277 14,253 14,336	14,288	38 35 36
E	TR	41,012 37,619 38,851	39,160	55 48 47
E	T	323,765 293,406 236,870	284,848	25 16 18
E	B	9,471 10,143 9,261	9,625	10 12 12
F	R	21,409 19,621 17,180	19,403	34 35 34
F	TR	22,755 23,310 26,193	24,086	55 52 52

TABLE II. (*Continued*).

Steel.	Treatment.	Number of Blows.	Average.	Resilience.
F	T	157,547 180,106 172,043	169,898	31 25 35
F	B	9,940 14,113 12,447	12,166	12 10 11
G	RL	56,897 63,188 73,211	64,432	18 25 23
G	T	30,041 36,674 31,059	32,624	50 47 53
G	B	6,420 7,975 5,725	6,706	5 0 0
H	R	102,956 155,470 111,654	123,360	30 24 23
H	TR	51,828 61,381 47,404	53,537	35 43 40
H	T	344,851 321,707 324,650	330,402	10 15 13
H	B	127,262 114,527 138,518	126,769	18 30 24
I	R	113,229 87,824 87,053	96,035	31 27 30
I	TR	58,464 59,473 57,598	58,535	18 24 23
I	T	100,060 89,991 79,282	89,777	8 11 13

TABLE II. (*Continued*).

Steel.	Treatment.	Number of Blows.	Average.	Resilience.
I	B	53,084 50,145 51,580	51,603	0 0 0
K	TR	53,270 62,864 76,089	64,077	30 30 27
K	T	170,571 156,051 141,945	156,189	8 7 12
K	B	77,085 131,200 123,885	110,723	0 0 0
II.—*Rate: 80 blows per minute. Fall: 1 inch (25·40 millimetres).*				
A	R	2,876 3,612 2,969	3,152	42 40 35
A	T	4,004 3,707 4,077	3,922	45 42 50
A	B	1,627 1,609 2,001	1,412	0 0 0
B	R	2,456 2,549 2,383	2,440	45 42 37
B	TR	2,604 2,500 2,742	2,512	57 55 57
B	T	3,800 3,475 3,514	3,595	50 45 47
B	B	1,779 1,856 1,406	1,680	30 25 35

TABLE II. (*Continued*).

Steel.	Treatment.	Number of Blows.	Average.	Resilience.
C	R	6,250 6,958 6,760	6,656	25 28 35
C	TRH	12,488 12,218 11,828	12,178	35 25 38
C	TRO	7,998 6,481 7,619	7,366	8 12 13
C	T	5,744 5,620 5,864	5,742	6 0 4
C	B	3,648 4,628 4,125	4,133	0 0 0
D	R	5,264 6,744 6,610	6,206	10 11 7
D	TRH	17,860 15,364 14,925	16,049	32 27 25
D	TRO	6,116 8,520 7,368	7,334	10 12 13
D	T	1 1 1	1	0 0 0
D	B	1,823 2,388 3,067	2,459	0 0 0
E	R	3,150 3,509 3,326	3,328	34 32 33
E	TR	6,838 8,660 6,444	7,314	37 45 40

TABLE II. (*Continued*).

Steel.	Treatment.	Number of Blows.	Average.	Resilience.
E	T	51,942 47,888 46,886	48,905	15 22 25
E	B	2,351 2,310 2,366	2,342	10 12 13
F	R	3,340 5,251 3,369	3,986	33 34 34
F	TR	5,629 4,902 4,420	5,007	40 40 44
F	T	8,445 12,154 8,518	9,705	22 27 25
F	B	3,962 2,905 3,314	3,395	15 14 12
G	RL	6,795 7,701 8,548	7,681	20 20 21
G	T	6,270 5,013 5,056	5,479	52 55 55
G	B	2,509 2,630 2,978	2,372	0 0 0
H	R	23,139 24,593 23,186	23,626	28 27 32
H	TR	11,903 15,330 14,001	13,744	45 40 38
H	T	18,048 15,011 16,786	16,615	17 22 20

TABLE II. (*Continued*).

Steel.	Treatment.	Number of Blows.	Average.	Resilience.
H	B	21,180 21,864 18,066	20,636	14 15 13
I	R	17,836 18,880 18,946	18,554	25 23 27
I	TR	17,080 13,691 16,512	15,761	20 22 23
I	T	21,138 18,370 22,279	20,594	10 9 12
I	B	4,101 4,033 3,429	3,854	3 0 5
K	TR	16,887 12,364 11,606	13,615	28 33 30
K	T	33,038 33,790 28,454	31,760	8 9 10
K	B	29,236 31,444 39,839	33,141	0 2 0
III.—*Rate*: 140 *blows per minute.* *Fall*: $\frac{1}{2}$ *inch* (12·7 *millimetres*).				
A	R	8,564 7,803 7,803	8,056	39 45 40
A	T	11,907 11,568 11,779	11,751	42 43 39
A	B	3,523 4,248 3,762	3,844	0 3 0

TABLE II. (*Continued*).

Steel.	Treatment.	Number of Blows.	Average.	Resilience.
B	R	6,700 7,196 7,846	7,264	38 38 39
B	TR	8,898 8,950 8,416	8,754	55 52 54
B	T	30;917 27,407 32,611	30,311	55 47 55
B	B	4,834 5,852 6,931	5,872	35 28 32
C	R	23,898 22,426 22,385	22,903	20 24 27
C	TRH	40,948 31,086 37,276	36,436	37 38 39
C	TRO	22,095 20,541 20,877	21,171	8 12 10
C	T	35,298 38,114 34,109	35,840	5 10 0
C	B	9,998 15,142 12,527	12,555	0 0 3
D	R	29,942 30,201 27,314	29,152	18 12 16
D	TRH	49,323 44,736 48,485	47,514	28 32 29
D	TRO	32,253 30,209 26,963	29,808	10 8 11

TABLE II. (*Continued*).

Steel.	Treatment.	Number of Blows.	Average.	Resilience.
D	T	2 2 2	2	0 0 0
D	B	11,767 13,297 9,390	11,484	0 0 0
E	R	6,457 6,368 6,872	6,565	43 42 47
E	TR	18,582 20,955 20,030	19,855	38 35 45
E	T	211,005 214,746 219,140	214,963	22 16 21
E	B	5,233 4,980 4,787	5,000	17 14 16
F	R	11,739 12,016 12,747	12,167	33 34 36
F	TR	13,127 11,860 11,353	12,446	42 41 39
F	T	108,091 130,542 102,390	113,674	27 20 25
F	B	7,630 7,292 7,125	7,349	15 12 13
G	RL	53,328 53,941 69,276	58,848	20 18 20
G	T	18,280 18,252 14,626	17,052	57 55 55

TABLE II. (*Continued*).

Steel.	Treatment.	Number of Blows.	Average.	Resilience.
G	B	3,437		5
		4,427	3,898	6
		3,830		4
H	R	100,874		27
		101,233	99,885	28
		97,548		27
H	TR	41,065		38
		37,037	35,490	43
		38,370		40
H	T	55,300		18
		52,247	48,806	19
		38,873		23
H	B	25,177		15
		36,192	30,171	16
		29,145		15
I	R	92,414		22
		88,977	92,608	25
		96,434		23
I	TR	40,991		26
		38,385	42,162	27
		47,111		22
I	T	41,292		12
		48,592	43,400	10
		40,422		9
I	B	22,881		0
		20,159	19,901	0
		16,665		2
K	TR	44,873		29
		37,399	42,795	30
		46,114		32
K	T	93,616		8
		84,450	87,980	7
		85,875		9
K	B	71,829		0
		71,861	65,987	2
		54,272		5

TABLE II. (*Continued*).

IV.—*Rate:* 140 *blows per minute.* *Fall:* 1 *inch* (25·4 *millimetres*).

Steel.	Treatment.	Number of Blows.	Average.	Resilience.
A	R	2,709 2,720 2,005	2,478	38 45 39
A	T	4,188 3,589 3,520	3,765	44 32 45
A	B	1,012 1,010 980	1,002	5 0 0
B	R	2,111 2,381 2,133	2,208	47 40 38
B	TR	2,175 2,114 1,921	2,070	55 55 55
B	T	3,274 4,020 4,290	3,861	55 48 43
B	B	2,197 2,147 1,730	2,024	35 37 25
C	R	5,251 4,977 5,306	5,178	22 21 24
C	TRH	9,467 8,063 9,317	8,949	34 37 34
C	TRO	4,527 4,987 5,093	4,869	12 15 8
C	T	6,109 4,177 3,793	4,693	0 0 0

TABLE II. (*Continued*).

Steel.	Treatment.	Number of Blows.	Average.	Resilience.
C	B	3,485 4,142 3,685	3,770	0 8 3
D	R	5,882 4,312 7,651	5,948	14 12 16
D	TRH	10,554 9,475 10,060	10,029	28 32 32
D	TRO	8,325 6,988 7,665	7,659	8 12 11
D	T	1 3 2	2	0 0 0
D	B	1,424 930 1,535	1,295	0 8 2
E	R	2,140 2,314 2,219	2,224	47 35 42
E	TR	4,336 4,732 4,651	4,237	40 40 39
E	T	11,049 18,792 14,434	14,758	25 15 19
E	B	2,402 2,375 2,742	2,506	14 17 18
F	R	2,695 2,621 2,515	2,611	38 29 34
F	TR	2,817 3,036 3,245	3,032	39 45 42

Table II. (*Continued*).

Steel.	Treatment.	Number of Blows.	Average.	Resilience.
F	T	6,974 7,299 6,424	6,899	20 23 27
F	B	2,072 1,984 2,083	2,046	12 0 18
G	RL	6,279 6,041 4,457	5,592	17 25 21
G	T	3,020 3,362 4,241	3,541	55 50 44
G	B	867 755 827	814	0 10 5
H	R	18,781 15,651 15,844	16,758	30 28 29
H	TR	10,812 10,736 10,128	10,558	45 44 37
H	T	19,052 21,655 23,619	21,442	15 24 19
H	B	13,259 11,918 14,219	13,132	15 16 12
I	R	13,925 13,628 13,062	13,538	22 16 19
I	TR	13,881 13,274 14,022	13,725	23 26 22
I	T	25,394 26,000 25,427	25,607	0 10 5

TABLE II. (*Continued*).

Steel.	Treatment.	Number of Blows.	Average.	Resilience.
I	B	2,744 3,122 2,765	2,877	0 0 0
K	TR	7,195 10,268 10,051	9,171	37 26 28
K	T	36,088 29,786 35,474	33,782	8 12 13
K	B	21,563 18,466 20,059	20,026	0 5 8

(2) ENDURANCE (ROTARY BENDING).

The stress to which, in the rotary bend test as practised by the author, the test-piece is subjected is comparable with the bending stress undergone by a piece of metal fixed at one end and loaded at the other. It is only necessary, therefore, to apply to it the well-known formula:

$$P = \frac{K}{L} \cdot \frac{J}{E}$$

where P represents the load; K, the strain within the material; L, the length of the test-piece; J, the moment of inertia of the test-piece; and E, the distance of the neutral axis from the furthest point.

For a test-piece of circular section $\frac{J}{E} = 0{\cdot}0982d^3$ (where $d =$ the diameter of the test-piece). In the test-piece used by the author $L = 110$ millimetres and $d = 13$ millimetres, whence—

$$P = K\frac{0{\cdot}0982 \cdot 13^3}{110} = K \cdot 1{\cdot}96.$$

K has always been taken as equal to $\frac{3}{5}$ of the elastic limit, the latter being determined by the degree on the diagram in

beam machines or the arrest-point of the mercury in mercury machines. Generally speaking, in determining the elastic limit, the Frémont 5-ton tensile machine has been employed.

The ultimate strain in the material is equal to the coefficient K, thus calculated *plus* a coefficient $K^1 = \frac{P}{S} = \frac{\text{load}}{\text{section}}$ representing the shearing stress, which has been disregarded.

TABLE III

Steel.	Treatment.	Endurance. No. of Revolutions.	Averages.	Resiliences.
B	R	789,000 914,000 842,000 964,000	876,290	38 49 39 41
P	R	1,723,000 2,914,000 1,978,000 1,820,000	2,008,790	30 39 38 38
C	R	7,994,000 7,911,000	7,732,900	27 24
Q	R	23,978,000 29,109,000 26,269,000 29,074,000	27,109,000	20 19 16 22
B	TR	2,314,000 2,627,000 3,189,000	2,708,660	99 99 99
P	TR	3.962,000 3,810,000 4,203,000	3,898,333	92 47 49
Q	TR	42,716,000 43,243,000	42,979,900	29 23
C	T	6,109,000	6,109,000	0

Table III. gives the results of these tests. These tests should, in the author's opinion, have related to the whole of

the steels to which reference has been made in former sections, but the length of time the experiments took have not permitted of his realising more than a small proportion of his programme. There have not been included in the table a certain number of results which were manifestly erroneous, due doubtless to vibrations arising from shocks coming from the works themselves or from tests carried out in the vicinity. Nor do they contain certain results which have been grouped together in a special table (Table IV.), and on which the author will have occasion to dilate further on. The figures relating to resilience have been obtained with test-pieces derived from the immediate prolongation of the endurance test-pieces.

(a) Results of the Tests.

Fig. 22 reproduces diagrammatically the result of the tests of Table III. From these it may be seen :—

1. That the resistance to rotary bending stresses (endurance) is proportional to the percentage of carbon, and that it even increases very rapidly with a relatively small increase in the amount of carbon.[1]

2. That quenching, followed by annealing, raises the resistance to rotary bending stresses.

3. That, however, this is not the case with quenching alone, so far as can be ascertained from a single test (steel C).

(b) Influence of the Brittleness of the Metal on its Resistance to Rotary Bending Stresses.

There does not, at first sight, exist any relation between the modes in which a metal behaves under the brittleness test and

[1] The author had the curiosity to case-harden an endurance test-piece of steel P to a depth of about 1 millimetre. After case-hardening the test-piece was quenched in water from a temperature of 850° and then annealed for fifteen minutes at 900°. This test-piece was then worked to $\frac{4}{5}$ of its elastic limit, the latter having previously determined in a Frémont machine on a tensile test-piece of 8 millimetres in diameter taken from a rod of 13 millimetres in diameter; this rod was case-hardened, quenched, and annealed together with the endurance test-piece. The results of this experiment, which are peculiarly suggestive, were :—

	Revolutions.
Endurance of the case-hardened test-piece	20,000,000
Resilience from test-piece taken from the core of the endurance test-piece.	30–35 (kilogrammetres.)

under the rotary bending tests. It is, however, necessary in this connection to repeat what has already been said as regards repeated shock tests and to confine the comparison to two true metals similar in all their properties save those two the variations of which are under investigation.

The following figures, compared with those of Table III., are particularly suggestive:—

TABLE IV.

Steel.	Treatment.	Endurance. No. of Revolutions.	Average.	Resilience.
B	R	{ 312,000 / 207,000 }	298,500	{ 8 / 5
P	R	49,000	49,000	0
C	R	{ 1,422,000 / 1,213,000 }	1,317,500	{ 2 / 0

It cannot be concealed that the foregoing apply to a few tests only; still, these tests may at least furnish some indication. It should be remembered that the necessity had arisen of examining two rails, one of which had broken in service, while the other had not, and the resistance of which to alternating stresses varied directly with the resilience under shock.[1]

These two rails had both remained in service, side by side, for twenty-five years. At the end of this period the former had broken and had been taken up; the second remained intact and was sent to the author as a check. Etching with iodine solution, carried out on a cross-section, revealed the existence of fairly pronounced segregation in the broken rail. The check rail only showed faint segregation. Brittleness and endurance tests carried out on the heads of these rails gave the following results:—

	Endurance. No. of Revolutions.	Resilience.	Sulphur per Cent.	Phosphorus per Cent.
Broken rail	534,000	3, 7, and 8	0·035	0·081
Check rail	11,225,000	12, 21, and 22	0·044	0·078

[1] *Sixth Congress of the International Association for the Testing of Materials* (unofficial report), Copenhagen, 1909.

These results, obtained on pieces actually in use, agree perfectly with those of the preceding table.

(c) Must a Steel have been worked beyond its Elastic Limit to Break under the Rotary Bend Test?

An exceedingly important question is to find out whether a steel which has broken under rotary-bending has been working truly and continuously below its elastic limit. The author has estimated the load under which his test-pieces were worked at $\frac{3}{5}$ their elastic limit. It may, however, be objected that the calculation is only approximately correct, and that besides, owing to shocks, vibrations, abnormal stresses, &c., the load, even if calculated correctly, may have exceeded the elastic limit of the metal—that which, repeated a certain number of times, has occasioned fracture. This mode of regarding the problem is the one which most machine designers adopt.

To settle the question it would, in the first instance, have been necessary to ascertain, by some perfectly accurate method, the elastic limit of the metal, and subsequently to provide against any extraneous stresses intervening in the course of the experiments. The first-named requirement would have involved the author in experiments he had neither the time nor the appliances for carrying out; the second was in part provided against by the interposition of buffers between the load and the test-piece. There is, however, an indirect method of solving the question, and that is to work the same steel, in one case annealed, and in the other quenched, under the same load, taken as an absolute value; that is to say, to suspend the same weight to two test-pieces, one annealed and the other hardened. The author was only able to carry out three experiments of this nature, the results of which are given in Table V.

Thus the same steel, the elastic limit of which varies in the ratio of 1 to 4, and in which the absolute value of the load does not appreciably vary, presents practically the same degree of endurance. So far, therefore, as the small number of the experiments justify the conclusion, there is reason to believe that a steel may break owing to rotary bending even if it has been worked below its elastic limit.

TABLE V.

Steel.	Treatment.	Endurance.	Resilience.	Elastic Limit in Kilogrammes per Square Millimetre.	Lead in Relation to the Elastic Limit.	Absolute Load.
C	R	7,994,000	27	32·7	60/100	38·9
		7,911,000	24	33·9	60/100	39·2
C	T	6,109,000	0	123·2	19/100	38·9
C	R	1,427,000	2	30·9	60/100	39·8
		1,213,000	0	33·7	60/100	39·6
C	T	1,227,000	0	127·8	14/100	39·8
C	R	9,264,000	39	39·4	60/100	41·6
C	T	7,980,000	0	129·2	16/100	41·6

(*d*) *Mode of Fracture.*

Figs. 35 to 37 show fractures of test-pieces by rotary bending. The fracture occurs by progressive fissuration in the same mode as that described in connection with fractures under repeated shocks. The test-piece breaks suddenly, yielding a crystalline fracture, as soon as the cross-section becomes too small.

(3) VIBRATIONS.

The author's first care in carrying out this new test was to make such arrangements that the metal should, as a matter of fact, be worked below its elastic limit; the importance of this consideration has been discussed in connection with the rotary bend test. A whole series of experiments were therefore undertaken in order to determine the elastic limit of bending, in the metals under investigation and for their various states (normalised, quenched, &c.).

With this object test-pieces of the same shape and dimensions, and held in the same way and in the same clutch as those intended to undergo vibratory stresses, were employed (Figs. 7 and 8). There was applied to the extremity of the test-piece a stress in the same direction as that which was to produce the vibratory movement, by means of a wire carrying

a hanging weight the amount of which could be varied as desired. The displacement of the free end of the test-piece was measured by means of a ray of light and of a scale placed at a certain distance. After having read the original position of the spot of light on the scale, the test-piece was loaded progressively, each additional load being allowed to exercise its influence for a period of thirty seconds. The load was then removed and it was seen whether the light-spot would resume its original position on the scale. The elastic limit was regarded as corresponding with the application of whatever load under which the light-spot underwent permanent displacement.

Figs. 23 and 24 show the apparatus employed. The load Q (Fig. 23), sustained by a pan suspended from a violin string, exercises its influence at the end of the rod under investigation by means of the arrangement shown in Fig. 24. This cord passes over a pulley r (Fig. 23), the axis of which rests on the rims of four other pulleys p and p' in order to reduce friction. The pulley r could, in addition, slide by friction in the direction of its axis so that, by moving it, it was possible always to maintain the wire perpendicular to the line xy. A mirror M fixed below the wire and carrying two graduated scales allowed of the degree by which the violin cord remained perpendicular to xy being ascertained. In addition to this the mirror served to determine, within about $\frac{1}{10}$ of a millimetre, the allowances for diminution in length $l-l'$ which would require to be made in calculating the bending movements. The end of the test-piece carried, in addition to the mirror m which reflected the luminous ray (Fig. 24), a thin needle (not shown in the figure) the displacement of which, along the graduated scale R′ (Fig. 23), gave these deflections under load to within about $\frac{1}{10}$ of a millimetre.

The load was increased by increments of 100 grammes and the position of the light-spot was observed (1) with the test-piece under load, and (2) with the load removed, and curves corresponding with these observations were plotted. All the curves obtained are closely alike in appearance. They are very regular, and a specimen of them is given in Fig. 26. As has been said, the elastic load was regarded as the first

load on the removal of which the light-spot no longer reverted to its initial position on the scale. The elastic load thus obtained coincided very closely with that under which the

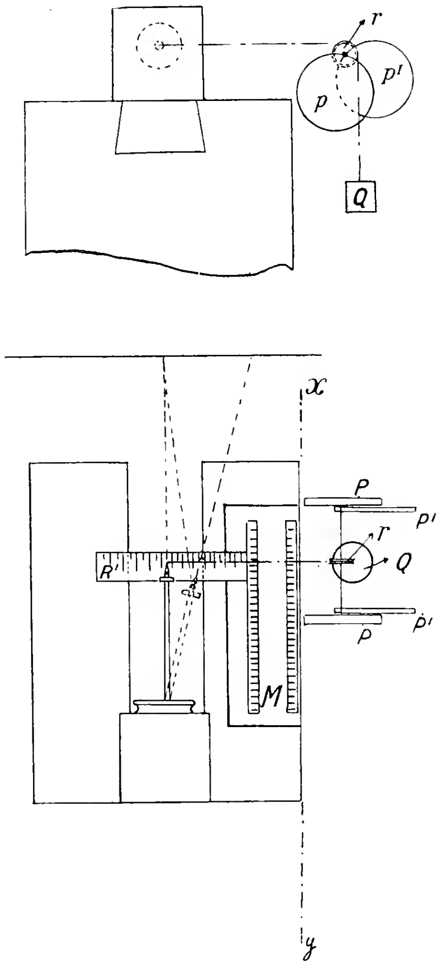


FIG. 23.

deformations under load ceased to be proportional to the stresses. The curves of deformation under load could not, however, be plotted in every instance, because, when the

elastic limit was very high, the light-spot fell outside the range of the scale.

The author has not failed to see that the absolute elastic load must be smaller than that which is here taken to represent it. The latter corresponds to the first deformation, and

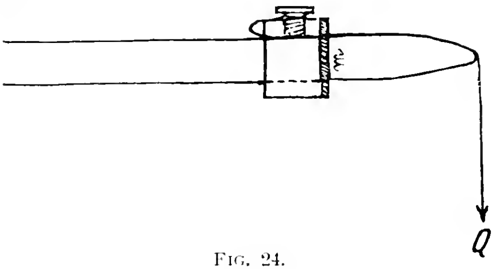


FIG. 24.

consequently the elastic load is, in terms of its very definition, exceeded. But he continued to adhere to this method of carrying out the test (1) because it is impossible to ascertain how much the absolute elastic limit is below the elastic limit as thus determined, and (2) because the identification of

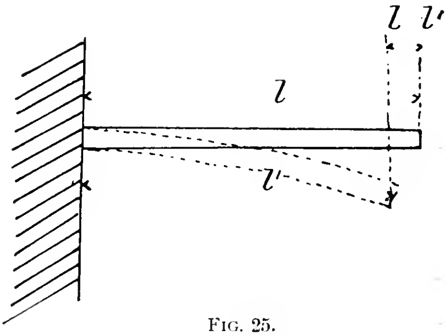


FIG. 25.

the elastic limit with the load corresponding with the first permanent deformation agrees with the mode by which the elastic load is always ascertained practically in works. The latter consideration meets the objection made by Résal,[1] inasmuch as the author's tests were carried out and calculated

[1] *Revue de Métallurgie*, 1911, vol. viii. p. 346.

under the same conditions as are the tests and calculations in works practice.

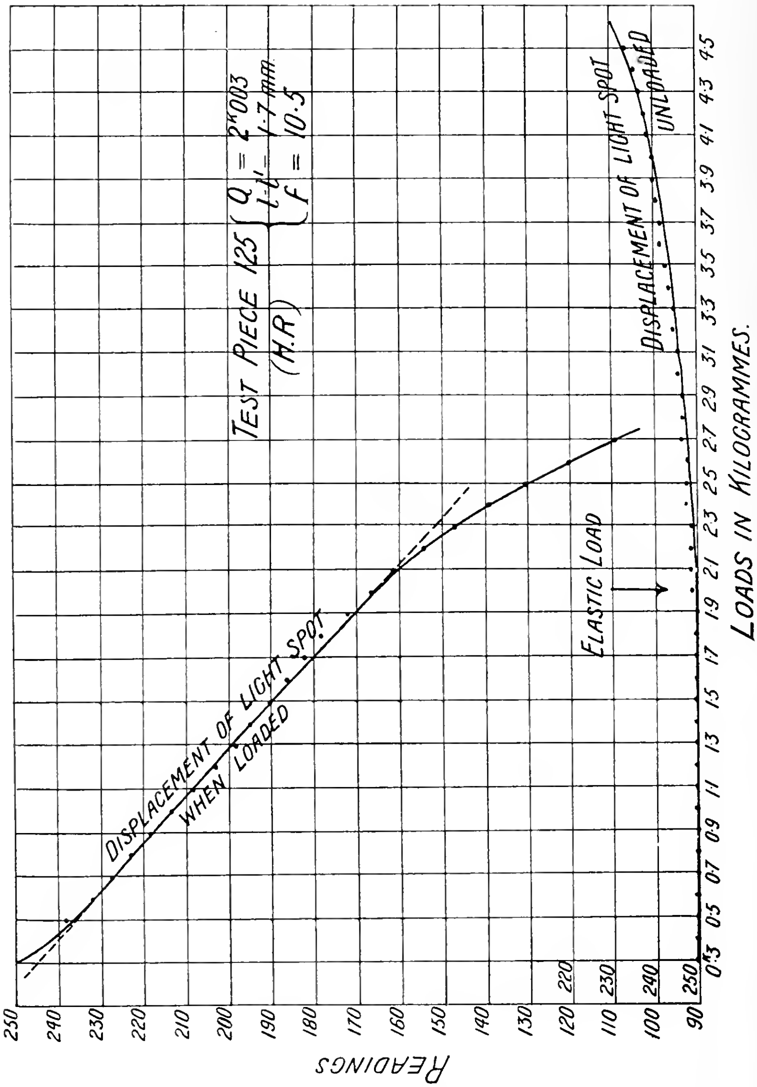


Fig. 26.

Table VI. gives details of the preliminary numerical results obtained.

TABLE VI.

Steel.	Treatment.	Elastic Load in Kilogrammes.	Average.	$l - l'$ at the Elastic Load in Millimetres.	Average.	Elastic Deflection in Millimetres.	Average.
B	R	1·175 [1] 1·505 1·329	1·336	... 0·2 0·2	0·13	5·7 7·5 7·0	6 7
B	TR	2·335 2·418 2·592	2·448	1·0 1·0 0·7	0·90	12·0 13·0 13·0	12·66
B	T	2·997 3·153 3·070	3·073	1·0 2·0 0·9	1·30	15·0 16·2 16·0	15·73
B	B	1·075 0·955 1·128	1·052	... 0·1 0·1	0·06	5·0 4·8 5·7	5·16
C	R	2·519 2·519 3·173	2·737	1·5 0·7 0·7	0·96	14·5 13·0 16·0	14·5
C	TR	2·811 3·505 2·940 2·909	3·040	1·1 1·2 1·7 1·3	1·32	15·0 16·0 16·2 16·1	15·82
C	T	4·519 4·997 4·335	4·617	1·1 1·4 1·4	1·2	23·0 23·5 26·5	24·3
C	B	2·084 2·475 2·325	2·294	0·9 0·8 0·5	0·73	12·0 13·5 11·5	12·3
D	R	2·436 2·353 2·000 2·000	2·197	0·5 0·5 0·5 0·7	0·55	13·0 13·0 11·0 11·0	12·0
D	TR	4·675 4·000 4·335 4·159	4·292	1·2 1·0 2·0 2·0	1·55	24·0 20·5 22·0 21·0	21·87

[1] The presence of decimal figures other than 0 may be due to the weight of the pan.

TABLE VI. (*Continued*).

Steel.	Treatment.	Elastic Load in Kilogrammes.	Average.	$l-l'$ at the Elastic Load in Millimetres.	Average.	Elastic Deflection in Millimetres.	Average.
D	T	4·519 5·827 5·329	5·225	2·5 3·2 2·7	2·8	25·5 31·5 28·0	28·3
D	B	2·219 2·114 1·984 2·000	2·079	0·5 0·9 0·7 0·5	0·65	11·0 10·0 10·5 11·0	10·4
E	R	2·592 2·242 2·242	2·358	1·0 0·9 0·9	0·93	12·5 12·5 11·5	12·16
E	TR	2·592 2·675 2·519	2·595	0·9 1·0 1·5	1·13	13·5 14·5 13·0	13·66
E	T	4·829 5·789 4·384	4·990	2·3 2·5 1·7	2·16	26·0 26·4 22·0	24·83
F	R	2·584 2·335 2·501	2·473	1·4 1·0 1·4	1·26	12·5 12·5 12·5	12·5
F	TR	2·584 2·086 2·169	2·279	2·5 1·5 1·0	1·6	13·5 10·5 10·5	11·5
F	T	1·754 1·754 1·837	1·788	1·7 1·7 1·7	1·7	9·0 10·0 10·0	9·6
H	R	2·003 2·335 2·335	2·231	1·7 1·0 0·9	1·2	10·5 12·0 12·0	11·5
H	TR	3·661 3·511 3·461	3·277	1·9 1·7 1·2	1·6	18·0 17·5 13·5	16·3
H	T	4·175 3·837 3·424	3·812	2·5 1·9 2·0	2·13	24·5 20·0 18·5	21·0

TABLE VI. (*Continued*).

Steel.	Treatment.	Elastic Load in Kilogrammes.	Average.	$l-l'$ at the Elastic Load in Millimetres.	Average.	Elastic Deflection in Millimetres.	Average.
I	R	3·090 3·497 3·659	3·497	1·0 1·2 1·3	1·16	17·5 17·5 19·0	18·0
I	TR	3·675 3·744 3·474	3·631	1·9 1·4 1·3	1·53	21·0 19·0 18·5	19·5
I	T	3·329 3·412 3·173 3·505	3·354	1·0 1·7 1·5 1·7	1·47	18·5 19·0 17·5 19·5	18·62
K	TR	4·000 4·083 5·000	4·361	2·2 2·2 2·2	2·2	19·0 20·5 25·0	21·5
K	T	4·519 4·000 4·000	4·173	2·7 2·0 2·2	2·3	24·0 21·5 21·5	22·3

All the test-pieces subjected to vibratory stresses were worked at $\frac{3}{4}$ of the elastic limit, as thus determined. For this purpose the electro-magnets were moved apart from one another for a distance equal to $\frac{3}{4}$ the amplitude corresponding with the elastic load; the amperage was adjusted so that the test-pieces could just touch, without appreciable jar, the cores of the magnets. It would appear, therefore, that in no instance could the effective bendings exceed or even attain the bendings corresponding with the elastic limits.

Table VII. gives the results of the vibratory tests carried out.

Table VII.

Steel.	Treatment.	Elastic Deflection in Millimetres.	Amplitude allowed in Millimetres.	Number of Vibrations.	Average.
B	R	6·7	10·5	275,000 287,000 278,000	280,000
B	TR	12·66	19·0	314,000 325,000 335,000	325,000
B	T	15·73	23·5	109,000 95,000 96,000	100,000
B	B	5·16	7·5	245,000 278,000 257,000	260,000
C	R	14·5	21·5	398,000 405,000 397,000	400,000
C	TR	15·82	23·5	1,020,000 1,040,000 1,100,000	1,090,000
C	T	24·30	36·0	45,000 48,000 55,000	49,000
C	B	12·3	18·0	211,000 192,000 197,000	200,000
D	R	12·0	18·0	2,413,000 2,428,000 2,366,000	2,402,000
D	TR	21·87	33·0	3,800,000 3,750,000 3,875,000	3,808,000
D	T	28·30	42·0	26,500 23,200 17,100	22,200

TABLE VII. (*Continued*)

Steel.	Treatment.	Elastic Deflection in Millimetres.	Amplitude allowed in Millimetres.	Number of Vibrations.	Average.
D	B	10·4	19·0	102,000 93,000 96,000	97,000
E	R	12·16	18·0	194,000 198,000 178,000	190,000
E	TR	13·66	20·5	177,000 184,000 179,000	180,000
E	T	24·83	37·5	15,900 19,200 24,700	19,900
F	R	12·5	18·0	854,000 857,000 831,000	844,000
F	TR	11·5	17·0	>5,000,000 >5,000,000 >5,000,000	>5,000,000
F	T	9·6	14·5	385,000 398,000 415,000	392,000
H	R	11·5	17·0	625,000 605,000 572,000	600,000
H	TR	16·3	24·0	417,000 391,000 392,000	400,000
H	T	21·0	31·5	3,125,000 2,950,000 2,925,000	3,000,000
I	R	18·0	27·0	197,000 183,000 191,000	190,000

TABLE VII. (*Continued*).

Steel.	Treatment.	Elastic Deflection in Millimetres.	Amplitude allowed in Millimetres.	Number of Vibrations.	Average.
I	TR	19·5	28·5	144,000 133,000 143,000	140,000
I	T	18·62	27·0	4,200,000 4,000,000 3,825,000	4,008,000
K	TR	21·5	32·0	92,000 95,000 86,000	91,000
K	T	22·3	33·0	>5,000,000 >5,000,000 >5,000,000	>5,000,000

(*a*) *Results of the Tests.*

Figs. 27 to 29 show diagrammatically the results reproduced from Table VII. On examining the diagrams the following conclusions emerge:—

1. In carbon steels—

(*a*) The resistance, in the annealed state, varies in direct proportion to the percentage of carbon; the rise in resistance, corresponding to a relatively slight increase of carbon, is considerable.

(*b*) Quenching markedly diminishes the resistance, but affects hard steels to a much greater extent than soft steels.

(*c*) Quenching followed by an annealing is the treatment that ensures the maximum resistance.

2. In nickel steels—

(*a*) The resistance, in the annealed state, varies in direct proportion to the percentage of nickel.

(*b*) Quenching reduces the resistance.

(*c*) Quenching followed by annealing gives the most marked resistance. The 2 per cent. nickel steel quenched and annealed is distinctly superior to the best carbon steel.

(3) In nickel-chromium steels—

(*a*) The resistance varies inversely with the hardness of

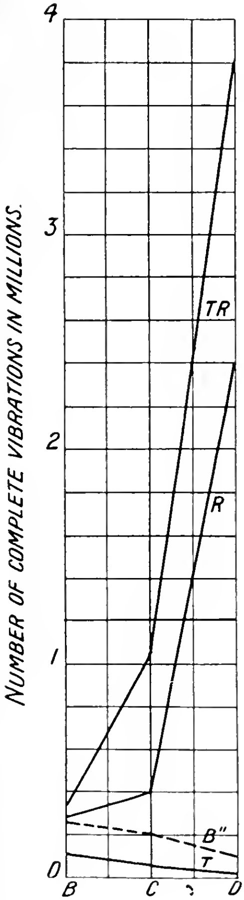


FIG. 27.

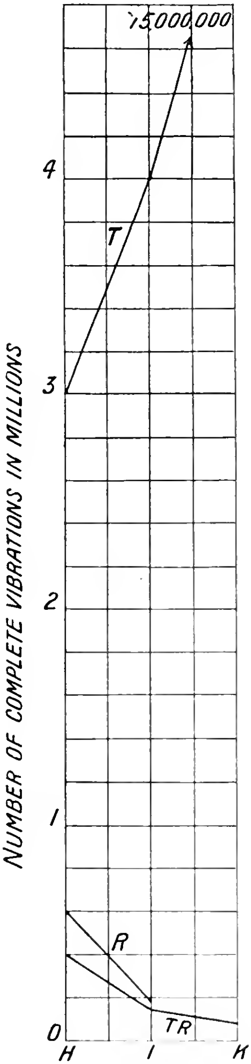


FIG. 28.

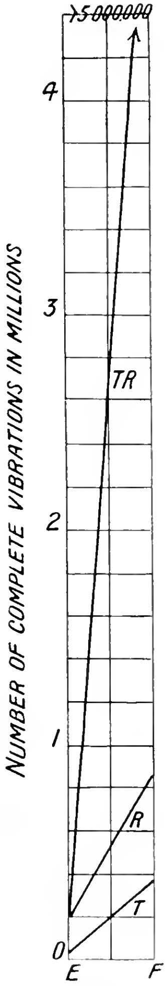


FIG. 29.

the steel, except in the quenched state. Hard nickel-

chromium steels quenched and annealed display less resistance than semi-hard steels, which again display less resistance than mild steels.

(*b*) In contradistinction to what occurs with carbon steels or with nickel steels, quenching considerably raises the resist-

FIG. 30.

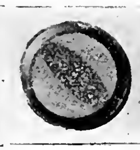


FIG. 31.

FIG. 32.

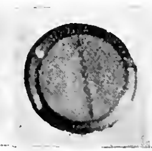


FIG. 33.

FIG. 34.

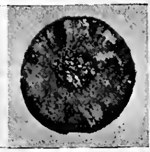


FIG. 35.

ance of nickel-chromium steels. It seems, moreover, to affect hard steel to a greater extent than it does mild steel.

(*c*) Quenching, followed by annealing, gives the minimum resistance. Any treatment that increases the tensile strength of nickel-chromium steel appears likewise to increase its resistance to vibratory stresses.

FIG. 36.

FIG. 37.

(4) An important fact is that all the steels, no matter what their nature (carbon, nickel, or nickel-chromium), ended by breaking, notwithstanding that they were being worked at less than their elastic limit.

Thus, a steel may break by vibration without its effective deflection having attained that calculated from its elastic limit.

It remains to ascertain what is the effective bending which

a rod may resist indefinitely, supposing such a bending amount exists. The author has, unfortunately, not had the time to bring this fresh investigation to a definite conclusion, although he has commenced it and will ultimately publish his results.

(b) *Influence of the Brittleness of the Metal on its Resistance to Vibrations.*

Lack of time similarly militated against the author making many experiments on this question, and in particular ascertaining how all the overheated steels behaved. He was able to experiment only on steels B, C, and D. In Fig. 27 the dotted lines give the results of tests carried out on these steels. Below are given the results of shock tests made on the same steels, both overheated and in the annealed state (normalised).

	B	C	D	
Overheated	30	0	0	Kilogrammes per
Annealed	41	25	45	square centimetre.

On examining the figures we are forced to the conclusion that overheating diminishes the resistance to vibratory stresses, and that this diminution is co-relative with a marked diminution in resilience.

(c) *Mode of Fracture.*

Figs. 38 to 45 reproduce fractures due to vibrations. These fractures are all alike and are perfectly characteristic.

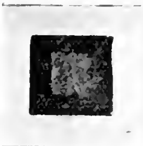


FIG. 38.

FIG. 39.

Breaking takes place by progressive cracking. When the flaw has been sufficiently developed it is exceedingly difficult to maintain the vibratory movement of the test-piece, but once

difficulties of this nature are encountered, fracture is not far off. The two pieces of the test-piece reach a stage where

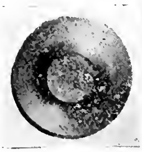


FIG. 40.

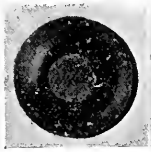


FIG. 41.

FIG. 42.

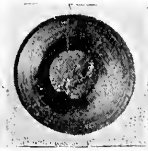


FIG. 43.

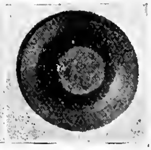


FIG. 44.

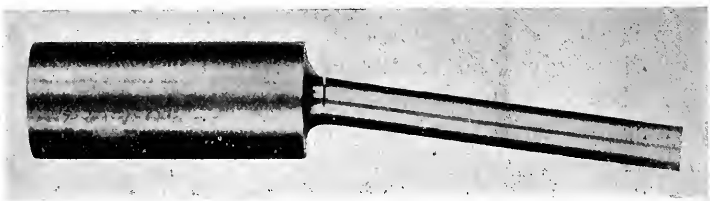


FIG. 45.

they are only held together by a narrow centre-band of metal which breaks, on the last stress, yielding a crystalline fracture.

(*d*) *The Relation between Bend Tests and Tensile Tests.*

The experiments undertaken in connection with vibrations have led to the elucidation of certain points, which while somewhat foreign to the scope of this report, it will be useful to place on record. From the tops of test-pieces which had served for the determination of the elastic limit of bending there have been made, in particular, tensile test-pieces with the object of ascertaining whether any relation exists between the bend test and the tensile test, so far as the elastic limit is concerned.

The tensile test-pieces were machined to a diameter of 7 millimetres. They were tested on a 5-ton Frémont machine. This machine was carefully tared, and loads corresponding with the horizontal portion of the curve of the diagrams in the annealed steels, or with the starting point of the curved portion of the diagrams in the quenched and annealed steels

and the steels only quenched, were taken as the elastic limits. The elastic limits on bending were calculated on the basis of the formula

$$P = \frac{K}{l} \cdot \frac{J}{e}$$

where

P represents the load to which the test-piece is subjected,
K the strain in the material,

FIG. 46.

FIG. 47.

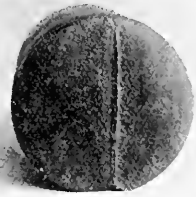


FIG. 48.

FIG. 49.

FIG. 50.

FIG. 51.

l the length of the test-piece ($= l^1$, Fig. 25),
J the moment of inertia of the section, and
e the distance of the neutral axis from the farthest fibre.

Table VIII. gives the results obtained.

Under the conditions of experiment in carbon steels the elastic limit of bending is comprised within—

$\frac{3}{5}$ and $\frac{4}{5}$ of the elastic limit on tension for annealed steels,
$\frac{4}{5}$ and $\frac{6}{5}$ for quenched and annealed steels,
$\frac{1}{2}$ and $\frac{6}{5}$ for quenched steels.

TABLE VIII.

Steel.	Treatment.	Elastic Load in Kilogrammes.	Average.	Elastic Limit of Bending in Kilogrammes per Square Millimetre.	Tensile Elastic Limit in Kilogrammes per Square Millimetre.	Average.	Ratio of Bending Limit to Tensile Limit.
B	R	1·175 1·505 1·329	1·336	18·73	24·0 26·8 24·4	25·06	0·74
C	R	2·519 2·519 3·173	2·737	38·25	47·1 48·0 48·2	47·76	0·80
D	R	2·436 2·353 2·000 2·000	2·197	30·75	51 2 53·3 47·1 47·1	49·67	0·61
B	TR	2·335 2·418 2·592	2·448	34·22	26·8 26·8 28·6	27·40	1·24
C	TR	2·811 3·505 2·940 2·909	3·040	44·42	50·7 49·6 54·4 56·0	52·77	0·84
D	TR	4·675 4·000 4·335 4·159	4·292	59·85	63·2 57·3 56·9 58·2	58·9	1
B	T	2·997 3·153 3·070	3·073	42·88	33·6 35·2 32·8	33·86	1 26
C	T	4·519 4·997 4·339	4·617	64·66	123·1 129·8 119·8	124·22	0·51
D	T	4·519 5·827 5·329	5·225	72·48	104·8 115·5 103·3	107·92	0·67
E	R	2·592 2·242 2·242	2·358	32·95	27·6 26·8 26·8	27·06	1·21

TABLE VIII. (*Continued*).

Steel.	Treatment.	Elastic Load in Kilogrammes.	Average.	Elastic Limit of Bending in Kilogrammes per Square Millimetre.	Tensile Elastic Limit in Kilogrammes per Square Millimetre.	Average.	Ratio of Bending Limit to Tensile Limit.
F	R	2·584 2·335 2·501	2·473	34·52	37·4 34·5 34·7	35·53	0·97
E	TR	2·592 2·675 2·519	2·595	36·24	36·5 37·2 38·8	37·50	0·96
F	TR	2·584 2·086 2·169	2·279	31·76	32·6 31·5 32·0	32·05	0·99
E	T	4·829 5·789 4·384	4·990	60·96	41·1 45·3 45·9	44·10	1·38
F	T	1·754 1·754 1·837	1·788	24·91	39·7 41·1 41·1	40·30	0·61
H	R	2·003 2·335 2·335	2·231	31·15	59·2 65·1 64·1	62·8	0·49
I	R	3·090 3·497 3·659	3·497	48·82	65·1 67·0 69·1	67·06	0·71
H	TR	3·661 3·511 3·461	3·277	45·68	56·0 50·9 53·0	53·3	0·85
I	TR	3·675 3 744 3·474	3·631	50·62	65·1 69·1 70·0	68·00	0·74
K	TR	4·000 4·083 5·000	4·361	60·64	60·6 60·1 59·7	69·1	1
H	T	4·175 3·837 3·424	3·812	53·02	?	?	?

TABLE VIII. (*Continued*).

Steel.	Treatment.	Elastic Load in Kilogrammes.	Average.	Elastic Limit of Bending in Kilogrammes per Square Millimetre.	Tensile Elastic Limit in Kilogrammes per Square Millimetre.	Average.	Ratio of Bending Limit to Tensile Limit.
I	T	3·329 3·412 3·173 3·505	3·354	46·77	120·08 121·60 118·56 ...	120·08	0·38
K	T	4·519 4·000 4·000	4·173	58·06	170 155 150	158·00	0·36

The ratio $\frac{\text{elastic limit on bending}}{\text{elastic limit on tension}}$ is always higher in mild steels than in hard steels. The elastic limit on bending exceeds the elastic limit on tension in hardened and annealed and simply hardened mild steels.

In nickel steels the elastic limit on bending is comprised within—

$\frac{5}{5}$ and $\frac{6}{5}$ of the elastic limit on tension for annealed steels,

$\frac{3}{5}$ and $\frac{7}{5}$ for hardened steels,

and is equal to the elastic limit on tension in steels hardened and annealed.

Finally, in chromium-nickel steels the elastic limit on bending is comprised within—

$\frac{1}{2}$ and $\frac{3}{4}$ of the elastic limit on tension in annealed steels,

$\frac{3}{4}$ and 1 in steels hardened and annealed,

and is equal to $\frac{2}{5}$ of the elastic limit on tension in hardened steels.

The net result is that, in proportion as the resistance of a steel to tensile stress increases, the elastic limit on bending differs more and more from the elastic limit on tension. In air-hardening nickel-chromium steels (steels possessing high resistance) the elastic limit on bending has nearly the same value after air-hardening as it had before.

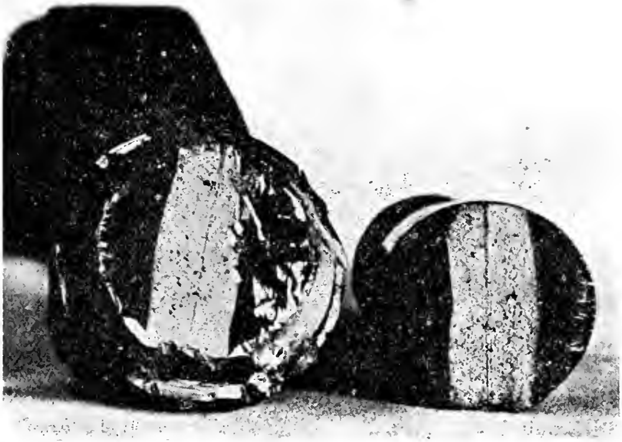


Fig. 52.

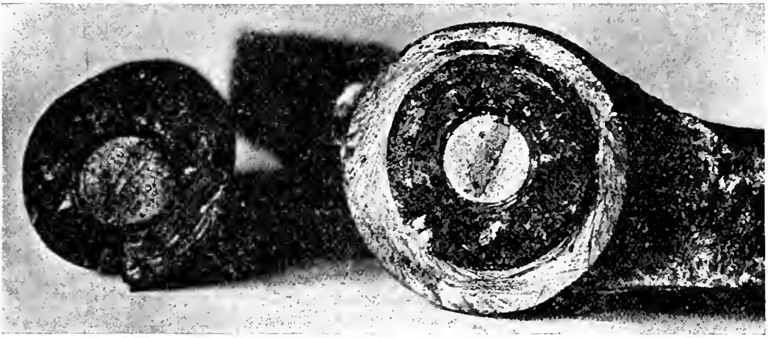


Fig. 53.

Fig. 54.

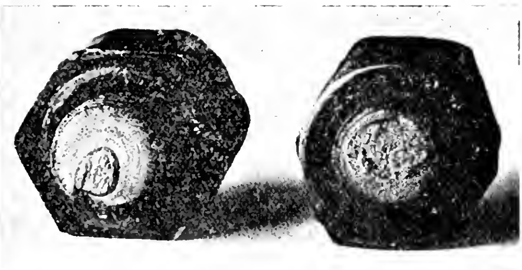


Fig. 55.

(e) *Moduli of Elasticity.*

This somewhat misleading fact is confirmed on considering the moduli of elasticity.

If we start with the formula—

$$f=\frac{P}{J}\cdot\frac{l^3}{3E}$$

in which

f represents the effective bend (deflection),
P the load to which the test-piece is subjected,
J the modulus of inertia,
l the length of the test-piece, and
E the modulus of elasticity,

and E be calculated on the basis of the actual results given in Table VI. for f and for P, the following values will be obtained for E:—

TABLE IX.

Steel.	Treatment.	Modulus of Elasticity in Kgs. per Sq. Mm.	Steel.	Treatment.	Modulus of Elasticity in Kgs. per Sq. Mm.
B	R	20,368,000	F	R	19,920,000
B	TR	19,554,000	F	TR	19,871,000
B	T	19,660,000	F	T	18,652,000
C	R	19,070,000	H	R	19,547,000
C	TR	19,334,000	H	TR	20,158,000
C	T	19,144,000	H	T	18,085,000
D	R	19,702,000	I	R	19,488,000
D	TR	19,487,000	I	TR	18,677,000
D	T	18,244,000	I	T	18,090,000
E	R	19,602,000	K	TR	20,190,000
E	TR	19,603,000	K	T	18,605,000
E	T	20,144,000			

It will be seen that the modulus of elasticity preserves an almost constant value, equal to 20,000,000 kilogrammes per square millimetre, no matter what the chemical composition of the steel may be or what treatment it may have undergone.

CONCLUSIONS.

The investigation may be summarised in a few lines and certain essential conclusions drawn from it.

Fig. 56.

Fig. 57.

Fig. 58.

Fig. 59.

Fig. 60.

Steels commonly employed in industrial practice have been taken as the starting point: structural carbon steels, steels containing a low percentage of nickel and combining high resilience with relatively high resistance, used for draw bars, motor-car axles, steering knuckles, and, generally speaking, all parts subject to dynamic stresses and requiring great safety; steels with high percentages of nickel employed more especially for valves in expansion engines; and chromium-nickel steels of the types employed in the motor industry and in ordnance.

These steels have been tested by rotary bending, by repeated impact, by simple impact, and by vibrations. The stresses have been calculated, when there have been any, by the same means as are ordinarily employed in practice, without attempting to conceal the fact that the absolute values themselves may have been different from the calculated values, but in the belief that more interesting results could be deduced than by taking, as a basis, experiments which, although perhaps more accurate, relate to conditions never attained in practice (Bauschinger mirrors, &c.).

The results of the investigation may be summed up as follows:—

(*a*) In the annealed state (normalised)—

The resistance to rotary bending stresses, to repeated shocks, or to alternating bending (vibrations) is proportional to the percentage of carbon in steels containing carbon lower than 0·25 to 0·30 per cent. Above this percentage the ratio between the percentage of carbon and the resistance becomes inverse as regards repeated shocks, but remains as it was in regard to rotary bending and alternating bending (vibrations).

Steels with a low percentage of nickel generally display a higher resistance to repeated shocks and to alternating bending (vibrations) than carbon steels. No experiments were made on rotary bending.

Steels containing a high percentage of nickel resist repeated shocks of small intensity remarkably well in an untreated condition. No experiments were made with rotary bending or with alternating bending.

The nickel-chromium steels offer a yet higher resistance

than nickel steels to repeated shocks and to alternating bending (vibrations). In the nickel-chromium series it is, however, the dead-mild steel which always displays the maximum resistance. No experiments were made with rotary bending.

(*b*) Quenching, followed by annealing, raises the resistance

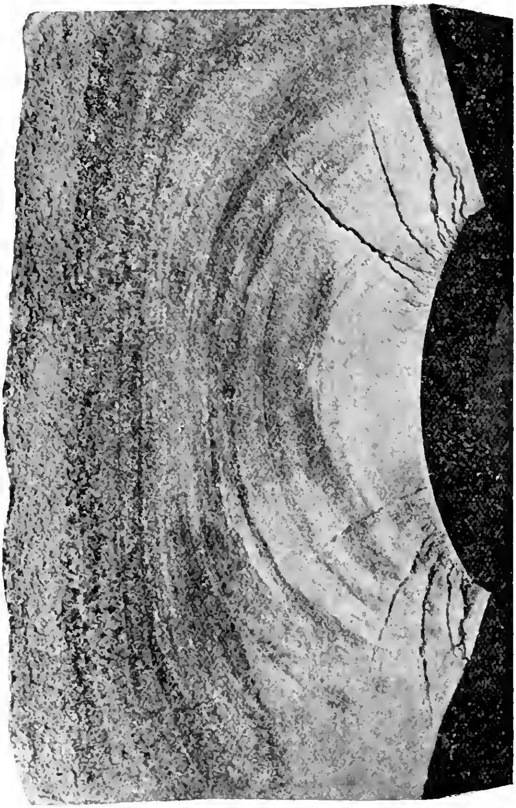


Fig. 61.

of plain carbon steels and of steels containing small percentages of nickel to repeated shocks and to alternating bending (vibrations). It tends to diminish the resistance of nickel-chromium steels. No experiments were made on rotary bending and on steels with high percentage of nickel.

(*c*) Quenching (not followed by annealing) raises the re-

sistance of mild carbon steels, and particularly of steels with small percentages of nickel, to repeated shocks. The nickel-chromium steels, particularly the soft nickel-chromium steels, also have their resistance increased to a notable degree. It diminishes the resistance of semi-hard nickel-chromium steels, and still more that of hard carbon steels with a high percentage of nickel.

Quenching (not followed by annealing) diminishes considerably the resistance of plain carbon steels and of steels with small percentages of nickel to alternating bending (vibrations). It raises, on the other hand, the resistance of nickel-chromium steels. No experiments were made on steels with high percentages of nickel or on rotary bending.

2. No matter what description of repeated stresses (rotary bending, alternating bending, repeated shocks) a metal be subjected to, it displays a better resistance thereto, in proportion, other things equal, as it displays resistance to the simple impact test for notched bars (the Frémont test).

3. No matter what description of repeated stresses a metal be subjected to (rotary bending, alternating bending), it may, even when working below its elastic limit, break, on the stress being repeated a sufficient number of times. It remains to be ascertained if fracture always occurs, irrespective of the amount of the stress, or whether there is a certain limiting amount of stress, below, be it understood, the elastic limit, at which resistance may be displayed almost to infinity.

4. No matter what description of repeated stresses a metal may be subjected to, it always fractures by progressive fissuration. The piece breaks suddenly when the section still remaining becomes too small.

In the accompanying plate has been grouped a certain number of illustrations of fractures caused by repeated shocks, rotary bending, and alternating bending (vibrations). The author has added thereto some fractures which have occurred under service conditions, and details respecting which are given below:—

Fig. No.	Cause of Fracture.	Nature of Steel.	Treatment.
30	Repeated shocks	Carbon steel	Annealed.
31–32	Repeated shocks	Carbon steel	Quenched and annealed.
33–34	Repeated shocks	Carbon steel	Quenched.
35, 36, 37	Rotary bending	Carbon steel	Annealed.
38–39	Alternating bending (vibrations)	Nickel-chromium	Quenched.
40–44	Vibrations	Various	Annealed.
45	Alternating bending (fissurations)	...	...
46–52	Fractures of steering levers, the fitting of which had been made with too much play (badly adjusted cones).		
53	Steering lever of motor lorry. This lever broke suddenly by vibrations due to a rough road. The driver mended it more or less effectively by boring the two broken ends of the pieces in the direction of their axes and inserting a pin, which he brazed in. This pin broke, in its turn, after running for 3 kilometres. The pin can be seen occupying the centre of the specimen.		
54	Lever for liberating the spring of the anvil in a Guillery impact test machine. The wide median band displays crystallisation.		
55	Bolts for holding on the slab mounted on the springs of a Frémont impact test machine.		
56–58	Shafts of a travelling bridge driven electrically and subjected to repeated shocks prior to the sudden stoppage of the bridge.		
59	Steam of a pneumatic hammer of **150** kilogrammes.		
60	Cottar of connecting rod of a gas-engine.		
61	Top of connecting rod of a gas-engine. This fracture recurs a considerable number of times in engines of this type. No other way of preventing this accident was found except to strengthen the parts and to replace the plain carbon steel by nickel steel.		

In these conclusions no account has been taken of the variation in the depth of fall or the speed of the alternation of the stresses in repeated shocks, which should be taken into consideration in comparing the relative results of bending and tensile tests, nor yet to considerations of the modulus of elasticity. On these points the reader is referred to the text itself.

INFLUENCE OF RIVETING ON THE STRESSES IN THE RIVET AND ON THE STRENGTH PROPERTIES OF THE RIVET MATERIAL.[1]

By HANS RUDELOFF, Dipl.Ing.

(Royal Testing Institute, Gross-Lichterfelde, Berlin).

The tensile stress prevailing in the finished rivet has to fulfil certain important functions, both in machine construction and in steel structures and bridges. Its chief purpose is to close the riveted portions together as tightly as possible in order to secure the utmost compactness, combined with a high resistance to slip. Tightness is mainly essential in the case of vessels built up of separate plates, such as boilers or gasometers, which are required to hold gases or liquids. In other kinds of structures tightness is necessary to prevent the penetration of the atmosphere and other destructive agencies likely in process of time to promote corrosion of the iron.

The resistance to slip is indispensable wherever stresses in members of structures are subject to change of direction or where loads are suddenly applied. Otherwise, since the rivet shanks never completely fill the holes, the riveted parts would continually vibrate, which would result in the gradual destruction of the shanks and sides of the holes. Much experimental research work has been performed to determine the amount of resistance to slip with different systems of riveting and various kinds of rivets. It is only necessary to refer to the work of Fairbairn, Bach, Frémont, Preuss, Rudeloff, and others. It has occasionally been considered whether the resistance to slip ought not to be taken into account in calculating the strength of riveted joints, but no practical method has ever been evolved, owing to the difficulty of finding a correct coefficient of friction, and to the fact that no trustworthy data are available concerning the stresses prevailing in rivets. The forces are therefore calculated only with reference to the resistance of the rivets to shear and the resistance of

[1] Received April 27, 1914.

the sides of the hole to frictional pressure. The resistance to slip which is also present is regarded as a useful accessory in preserving the shank and sides of the hole against the effect of shock and also as a means for securing that the riveted parts receive their uniform share of the load. Even with a more accurate knowledge of the stresses occurring in rivets it would hardly be wise to take account of these in calculating the strength of the joint, since it is uncertain whether they remain constant for long. In view of the importance of the question, some knowledge of their value and of the extent to which this value is dependent upon the method of riveting and on the time expended on the riveting operation is, however, of general interest.

The first experiments for the measurement of the tensile stress in rivets were described by M. Rudeloff in 1910.[1] Data were given as to the change in the strength properties of the rivet material, but unfortunately no information is furnished as to the method of making the rivets used in countersunk riveting. In 1912 Bach and Baumann published the results of an extensive series of experiments on the influence of the hydraulic riveting press on the longitudinal stresses in the rivet.[2] Early in 1912 the author, in his capacity as assistant at the Royal Testing Institute at Berlin-Lichterfelde, carried out a small series of tests on the influence of various methods of riveting, namely, by hand, by pneumatic hammer, and by the toggle-lever press, on the tensile stresses in rivets, the results of which inspired him to undertake the present research. The scope of the investigation has been considerably widened and extended to the examination of the changes produced in the material by the different methods of riveting. The grant of a Carnegie Scholarship of the Iron and Steel Institute, together with the permission to make use of the apparatus of the Department No. 1 for testing metals at the workshop of the Testing Institute, enabled him to carry out an extensive series of experiments. The

[1] M. Rudeloff, "Materialfestigkeit und Zugspannung im fertig geschlagenen Niet"; *Dingler's Polytechnisches Journal*, 1910, Nos. 26 and 27.

[2] v. Bach und Baumann; *Zeitschrift des Vereins deutscher Ingenieure*, 1912, vol. lvi. pp. 1890–1895.

material for the tests was most generously supplied by the bridge-building department of the Dortmund "Union."

I. SCOPE OF EXPERIMENTS.

As already indicated, it was decided to determine in definite values the influence of riveting (1) by hand, (2) by pneumatic hammer, (3) by the riveting press, on the magnitude of the tensile stress in the cold rivet after having been riveted hot. At the same time the changes in the strength properties of the rivet material were to be investigated. In order to attain as nearly as possible to the conditions of practice in bridge building and structural work, to which primary consideration was given, rivets of three different lengths were taken, namely, $l = 1{\cdot}5d$; $l = 3d$; and $l = 5d$. The time effect of the work on the rivet while riveting was studied by fixing three scales of time for the duration of the riveting operation. In determining these scales regard was had to the circumstance that in practice it is impossible to maintain absolute uniformity in the time expended in riveting each individual rivet. The time limits of a large number of riveting operations performed by many different workmen were therefore carefully measured with a stop-watch and the averages approximating most nearly to the time scales chosen were taken, it being considered that three such periods of different duration would be sufficient for the elucidation of the time effect. As the available resources to cover the cost of the experiments were limited, these observations were confined to the rivets with a length of shank equal to three diameters. For the same reason all the tests were made with rivets of the same diameter, namely, 20 millimetres. Since the conditions under which the rivet cools govern the degree of tensile stress, it was decided, in addition to the tensile tests at room temperature, to test the material at the temperature the rivet would have at the end of the riveting operation, that is, about 500° to 600° C.

The Test Material and its Preparation.

The method of preparing the test specimens is clearly shown in the general plan of the work presented in Table I. Mild steel rods of 19 millimetres diameter were used for the rivets. For the determination of the tensile properties of the rods before riveting, one rod 2 metres (6 feet 6 inches) long and 12–10 inch long snap-headed rivets were supplied with the other material. The riveted test specimens were of ordinary good workmanship. The holes were bored and reamed out clean to 20 millimetres diameter. As shown in Table I., the specimens were numbered 1 to 15, and consisted of groups of three rivets, each marked A, B, and C, according to the order in which they were driven. The riveting of the three rivets in each group was performed under as nearly identical conditions as

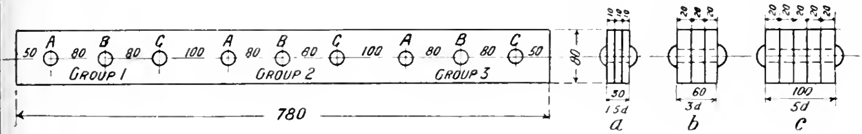


Fig. 1.—Shape of the Riveted Test-pieces.

possible, this number of rivets being considered sufficient for obtaining trustworthy data. The form of the test-pieces is shown in Fig. 1. They were made up of well-dressed flat strips of plate 80 millimetres wide by 10, 15, and 20 millimetres thick respectively, which were piled to at least three thicknesses (or more if necessary) to take the rivets of the various lengths. The pitch of the rivets in each group was 80 millimetres, and the distance between the outside rivets of two groups was 100 millimetres, while that from the outside rivet of all to the end of the strips was 50 millimetres. The shape of the rivet head is shown in Fig. 2.

The riveting was performed in July 1913, in the presence of the author, in the bridge-building department of the Union Works, Dortmund. All the rivets throughout their whole length were heated bright red (about 900° to 950° C.). In each system of riveting employed the rivets were driven directly one after another, and the plan adopted was, that,

in the case of the rivets marked "normal" (Table I.) it was left to the judgment of the leader of the riveting gang to decide the length of time expended on the rivets of a length equal to 1·5, 5, and 3 diameters. The time spent in closing each rivet was measured by the author with a stop-watch. Afterwards the author noted the longer or shorter riveting times in the other groups. In hand riveting it was noted that notwithstanding that the times were often approximately the same, the number of strokes, which were at first counted but not recorded varied considerably (by as much as 7). Accordingly, in riveting the groups 5 and 6 the number of

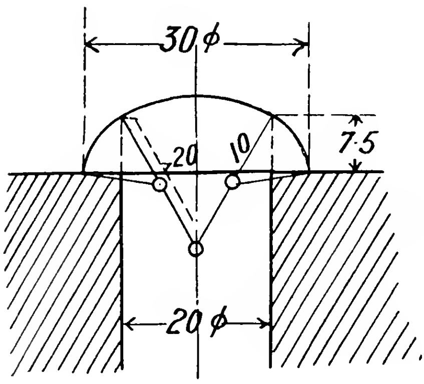


FIG. 2.—Rivet Head. Full Size.

strokes were counted and recorded as 20 and 30 respectively, without reference to the time.[1]

Small variations in the riveting time and in the number of strokes in the same group could not be entirely avoided because, owing to the noise in the erecting shop, the orders were not immediately understood. In the case of hand riveting and the pneumatic hammer the times are measured from the moment of the first blow until the last. With the riveting press they are measured from the moment of closing the die on the rivet until the pressure is released. For hand

[1] The hand riveting was performed in the usual manner, the point being first beaten down roughly with hand hammers, and the snap-head was then formed with a set and sledge hammers. The times and number of strokes refer to the latter process. The rough beating down took 8 to 10 seconds.

TABLE I.—*Method of Preparation of the Specimens.*

Rivet Group No.	Particulars of Rivet.				Preparation of the Rivet.								Remarks.
	Arrangement of Test Specimens according to Fig.	Material.	Length of Shank in Millimetres.		Method of Riveting.	Length of Riveting Time.				No. of Strokes for Rivet.			
			Before Riveting.	After Riveting.		General.	In Seconds for Rivet.						
							A	B	C	A	B	C	
1					Hand hammer . .		34	30	30	?	?	?	
2	1*a*		56	1·5*d* =30 mm.	Pneumatic hammer	Normal	12	13	13	...	...	...	
3					Lever press . . .		3·5	2·5	2·0	...	...	...	
4						Normal	**32**	**27**	**23**	?	?	?	
5					Hand hammer . .	...	20	25	26	20	21	20	
6						...	26	31	33	20	30	30	6A. One hand-riveted head broke off.
7						Normal	**10**	**12**	**10**	...	...	...	
8	1*b*	Mild steel	90	3*d* =60 mm.	Pneumatic hammer	...	8·4	8·0	8·4	...	...	...	
9						...	15·4	15	15·0	...	...	...	
10						Normal	**3·0**	**2 0**	**2·5**	...	...	...	
11					Lever press . . .	...	5·0	5·0	6·0	...	...	...	
12						...	7·6	7·6	7·6	...	...	...	
13					Hand hammer . .		38	38	35	36	**32**	26	
14	1*c*		130	5*d* =100 mm.	Pneumatic hammer	Normal	17	14	14	...	...	...	
15					Lever press . . .		3	2	2	...	...	...	

and pneumatic riveting the rivet was held up by a counter-set, lying on an anvil, and in riveting with the press no appliance was used for first pressing the plates together. The pressure applied by the compressed air lever press was 55 tons.

METHOD OF CARRYING OUT THE TESTS.

I. *Determination of the Rivet Stresses.*—The tension on a rivet is produced by the riveted plates preventing the contraction of the rivet in cooling. By removing the obstacle and allowing the rivet afterwards to contract, the tension previously existing in the rivet may be approximately determined by measuring the amount of shrinkage. If l denotes the length of the shank in millimetres of the rivet when cold, that is, the thickness of the riveted plates between the rivet heads, λ the shrinkage of the rivet after release, and l_0 the length of the released rivet, then—

$$(1) \qquad l_0 = l - \lambda.$$

Further, let σ equal the stress in kilogrammes per square millimetre of rivet section, and E the modulus of elasticity in kilogrammes per square centimetre. Then—

$$(2) \qquad \sigma = \frac{\lambda . E}{l_0} = \frac{\lambda . E}{l - \lambda}.$$

It is assumed that the section of rivet shank is equal throughout, which is approximately true for rivets of short and medium length. Since λ is very small in proportion to l (about 0·1 per cent. of l), the equation may with approximate accuracy be expressed thus—

$$(3) \qquad \sigma = \frac{\lambda . E}{l}.$$

The measurement of the shrinkage cannot, however, be taken direct on the shank if the condition of stress in the test-piece is to remain undisturbed. It is necessary to measure the change of total length, including the rivet heads. The values thus obtained include, therefore, the change of shape of the heads as well. This can be allowed for in calculating

the stress by referring the experimentally ascertained change of shape of the head in the axial direction to that of a portion of the shank, whose ideal length l_1 is easy to calculate. There being two rivet heads, the equation then becomes—

$$(4) \qquad \sigma^1 = \frac{\lambda \, . \, E}{l + 2l_1}.$$

Expressing l and l_1 respectively as n and μ functions of the shank diameter d, then—

$$(5) \qquad \sigma^1 = \frac{\lambda \, . \, E}{(n + 2\mu)d}.$$

The shrinkage of the rivet was measured as follows:—With a hardened steel centre punch having a point sharpened to an angle of 90°, punch marks 2 millimetres deep were struck in the top of the rivet heads. A Brown and Sharp micrometer screw of very good make, on the drum of which the scale was marked in divisions of 0·01 millimetre, was used for measuring all the rivets, and it was easy to estimate a variation to within 0·001 millimetre. Readings were taken to 0·001 millimetre of accuracy, which corresponds to a stress σ approximately equal to

$$\frac{0{\cdot}001 \, . \, E}{l} = \frac{0{\cdot}001 \times 21250}{l}.$$

The degree of accuracy for $l = 1{\cdot}5d$, $3d$, and $5d$ may be accordingly calculated at 0·7, 0·35, and 0·2 kilogramme per square millimetre. The measuring faces of the screws were fitted with caps carrying hardened steel balls 2 millimetres diameter, which were bedded in the punch marks. Fig. 3 illustrates the method. In repeating the measurement, the balls were adjusted again in the same manner in the punch marks, so that the same circle of contact between ball and punch mark was always preserved, and irregularities in the position of the measuring instrument in relation to the specimen were obviated as far as possible. This arrangement has the advantage that the points of contact for the measuring instrument are less exposed to damage during the further operations on the test-piece than they would be if the

measurements were made on the surface of the rivet heads. Any grease or dust that might affect the accuracy of the results could easily be removed. By inserting lengthening pieces the micrometer screw could be set to various ranges, and in order to avoid any error due to altering its range, rivets of one length only were examined at one time. The accuracy of the measuring instrument was continually checked

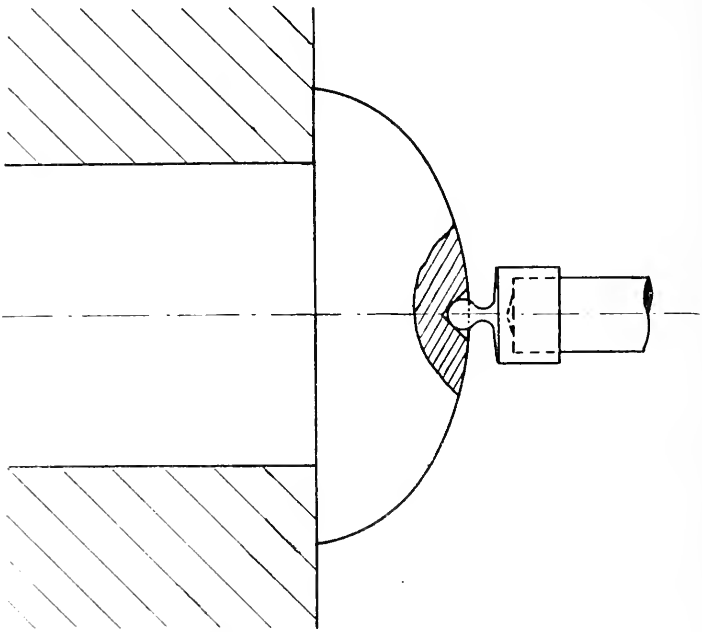


FIG. 3.—Measurement of Shrinkage. Double Size.

by means of a gauge, and the measuring was performed in a room specially arranged for the purpose, with as nearly as possibly constant temperature, in which the specimens were allowed to lie for at least two days before they were handled. Each rivet was measured in three different conditions, namely, as delivered after riveting, after cutting up the test-pieces into single riveted pieces, and after removal of the resistance of the riveted plates. A series of five measurements was performed in each case, after ascertaining that repeated measurings,

on different days, of the groups 13, 14, and 15 with $l=5d$ had given the same average results. The cutting up of the specimens into single riveted pieces was done with a cold saw, and the resistance of the riveted plates was removed by turning a groove 5 millimetres wide out of one of the plates until the rivet shank was reached. On completion of this, the remaining plates could be easily moved, so that the rivet shank was quite free. In turning out this groove the lathe chuck gripped one plate only by the extreme edge, and the tool was set to cut the groove out of the same plate, by which precaution any possibility was avoided of the plates rubbing against each other and producing torsional stress in the rivet (see Figs. 4 and 5). This mode of operation had the disadvantage that it was long and costly. In both sawing and turning great care was taken to prevent any undue heating of the material.

The total thickness of the riveted plates, even in the case of the short rivets, did not vary from the prescribed thickness by more than 0·5 per cent., so that it was thought unnecessary to allow for this slight difference, and the stress was calculated on the prescribed length.

The determination of the elongation of the head in the direction of the rivet axis, or the ideal length l_1 was performed on one of the unused rivets 19 millimetres long which were delivered along with the riveted work, and on another rivet 23 millimetres diameter left over from some other experimental work. The elongation λ_N of the upper part of the rivet, including the head, was measured direct, and from this value the elongation λ_S of the part of the shank included in the measurement was deducted, l_S being calculated from the modulus of elasticity which had been determined on the rivet itself. The difference of the two values gives the portion of elongation for the head λ_K thus—

$$(6) \qquad \lambda_K = \lambda_N - \lambda_S.$$

The length of a part of the shank corresponding to this elongation, the ideal shank length, is then—

$$(7) \qquad l_1 = \frac{\lambda_K \, . \, E \, . \, F}{P},$$

or referred to the shank diameter d—

$$(8) \qquad l_1 = \mu \, . \, d, \text{ in which } \mu = \frac{\lambda_K \, . \, E \, . \, F}{Pd},$$

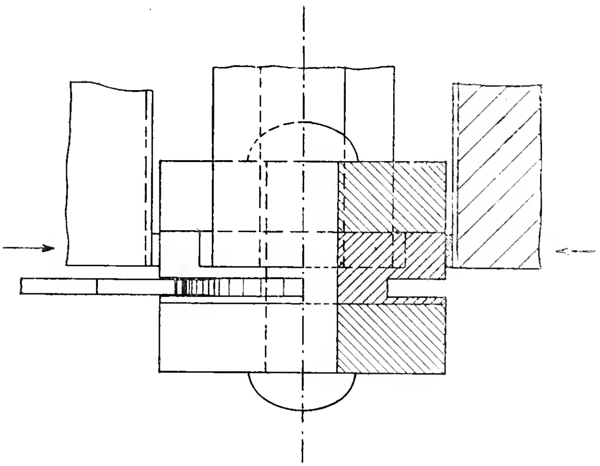


Fig. 5.

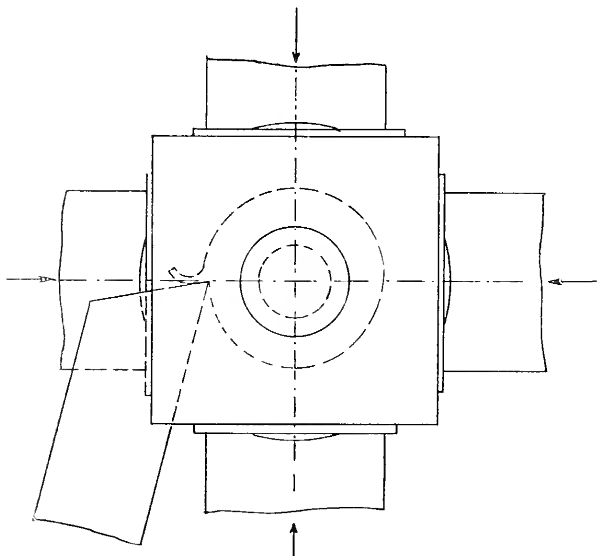


Fig. 4.

Showing Method of cutting Groove in the Plate to release Tension on Rivet.

in which F denotes the section of the shank immediately under the head, and P the load.

The tests themselves were carried out on one of the 50-ton tensile testing machines of the Martens type in the laboratory, which are specially suitable for the purpose. The method of gripping the rivet is illustrated in the photograph (Fig. 6). As the bore in the upper clamp was larger by 1·5 and 5·5 millimetres respectively than the rivet diameters of 23 and 19 millimetres, special bushes, 20 and 30 millimetres high, and bored exactly to the rivet diameter, were placed under the rivet head, while the shank was centred accurately in the clamp with pasteboard wrappings. Tin foil washers 0·3 millimetre thick were placed under the unmachined surfaces of the rivet heads to enable these to bed themselves well on the edges of the bushes. The plain end of the rivet was screwed and attached to the lower clamp by means of a nut and bolt.

The modulus of elasticity of the shank was determined in the usual way by means of the Martens mirror apparatus and measuring springs 80 millimetres long, which were attached direct to the shank. Fig. 6 also shows the arrangement of the measuring apparatus for the determination of the elongation of the head. A small hole 3 millimetres deep and 2·5 diameter was made in the top of the rivet head, into which a plug was firmly driven. The upper part of the plug supported a circular disc of 100 millimetres diameter, the edge of which was provided with a groove for receiving the tips of the measuring springs. Below the clamp, and fixed to the rivet shank by means of three set screws, was a ring plate 1·5 centimetre thick, 28 millimetres internal diameter, and with an external diameter of also 100 millimetres. The hardened points of the set screws were entered in a ring notch cut round the shank. In this manner the movement of the rivet cross-section at the notch could be measured as against the top of the rivet head carrying the disc, by means of four straight measuring springs extending from disc to disc and the Martens mirror apparatus. In order as far as possible to obviate errors due to uneven adjustment of the instrument, its position was continually changed. The average values found for the four points of observation agreed remarkably well. For striking an average, only those series of readings were taken in which the differences in the readings remained

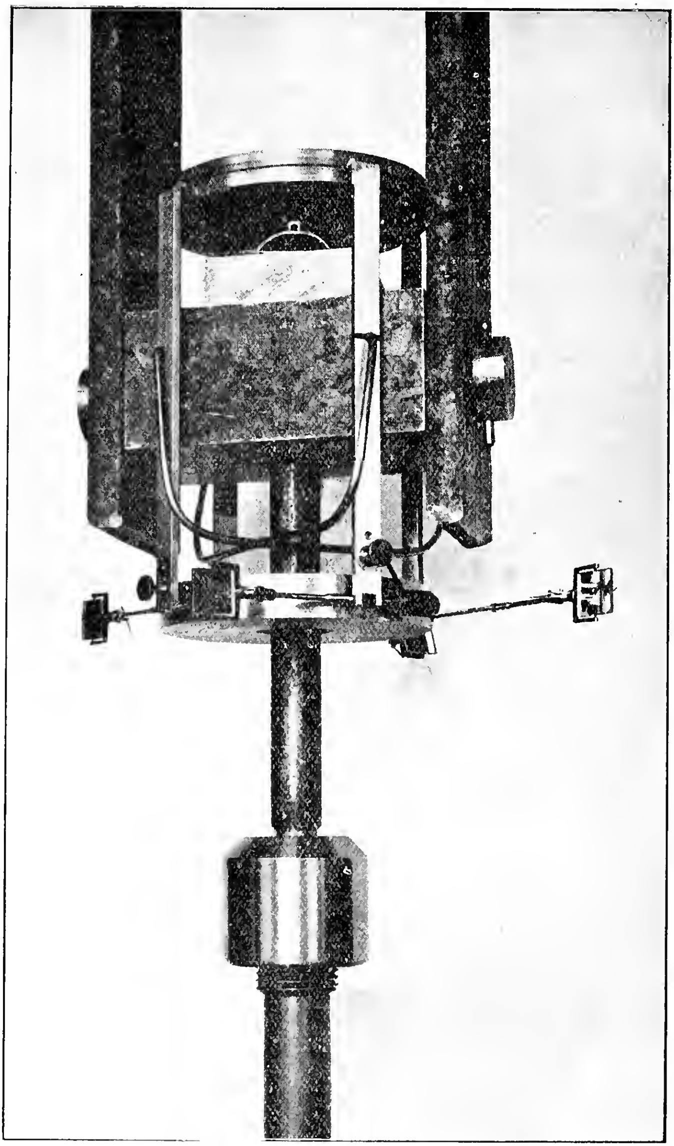
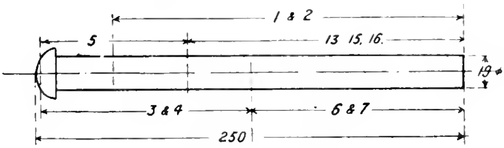


FIG. 6.—Determination of the Elongation of the Rivet Head. Arrangement of the Measuring Apparatus.

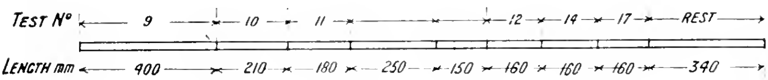
within the limits of $\pm$ 1 centimetre $\times 10^{-5}$. In the case of certain series of tensile tests it was ascertained, by a graduated increase of the load, that the limit of proportionality within the range of the test was not exceeded.

II. DETERMINATION OF THE STRENGTH PROPERTIES OF THE RAW MATERIAL AND OF THE DRIVEN RIVETS.

For this purpose tensile tests, shear tests, and ball pressure hardness tests were made. Figs. 7 and 8 show how the test specimens were prepared from the material supplied. With regard to the tensile tests on driven rivets, since the machine could not take rivets of 19 millimetres diameter, only one test-bar of the full diameter of 19 millimetres was taken from the round rod of rivet iron which was supplied with the other



ROUND ROD Scale 1:10



FIGS. 7 and 8.—Showing Size and Position of Tensile Test Bars in relation to Rivet and Rod from which they were cut.

material. Test-bars of 14 millimetres were prepared from the driven rivets, and all other test-bars taken from the round rivet rod and unused rivets for testing at room temperature had the same diameter. For the tests at higher temperatures, however, the diameter of all the bars had to be reduced to 10 millimetres on account of the limited size of the heating furnace.

In order to ascertain whether the strength of the material

at the outside of the rod differed in any way from that of the core, another test-bar 10 millimetres diameter was prepared from the rod and tested at room temperature. The length between points of measurement in experiments 1, 2, 8, 9, 10, and 11 was fixed at $11{\cdot}3\sqrt{f}=10d$. The measured length of the test-bars Nos. 3, 4, 5, 6, and 7 was $5{\cdot}65\sqrt{f}=5d$. In experiment No. 5, and in all the test-bars taken from the driven rivets, the measuring length had to be adjusted to the available length of the material, being made equal to n times half the diameter of the bar (7 millimetres). In all the tensile tests, including those at higher temperatures, the modulus of elasticity E, the limit of proportionality P, and the yield-point S, were determined by means of Martens' mirror apparatus. The ultimate elongation δ was measured on the lengths of $11{\cdot}3\sqrt{f}$, $5{\cdot}65\sqrt{f}$, and $2{\cdot}26\sqrt{f}$, in order to get a comparison between all the tests. In the case of those specimens which broke outside the middle third, the division marks which were lacking towards that end were added in the usual way. Half the test-bars for the tests at higher temperatures (up to 600° C.) were taken from the round rod and the other half from the unused rivets. For the experiments up to 300° C. cylinder oil was used for the heating bath, and for higher temperatures Chilian nitrates and nitrate of potassium were used.

The specimens for the shear tests were given as nearly as possible the same diameter as the tensile test-bars, the actual diameter being 13 millimetres in order to suit the apparatus in the laboratory. Their length was three times the diameter and they were tested in double shear.

In preparing the specimens for the ball-pressure test the material was planed down on one side to a surface equal in width to the diameter, and on the other to one of 8 millimetres width, and the surface corresponding to the diameter was polished. Before performing the hardness test all the cut surfaces were etched with copper ammonium chloride in order to ascertain how the beading over of the heads had been effected by the three riveting methods, and whether differences due to the different lengths of time expended in riveting could be detected.

The hardness tests were performed on a Brinell ball-pressure machine built by the Aktie Bolaget Alpha. The steel balls were 10 millimetres in diameter, and the pressure of 500 kilogrammes was maintained for exactly two minutes. In calculating the hardness number, only the area of the circle of impression was taken into account. The impressions were distributed as uniformly as possible over the whole surface, care being taken that the distance from the centre of any impression to the edge of the specimen was not less than 2·5 times the probable diameter of the impression, in order not to affect the accuracy of the determination.[1]

Of the driven rivets those marked A were used for the tensile tests, those marked B for the hardness determinations, and those marked C for the shear tests. Since in group 6 rivet A had only received 20 strokes, rivet No. 6, which had received the correct number of 30 strokes, was also subjected to the tensile test. The shear test was not performed on this group, nor on group 10, since here too rivet C had to be tested for tensile strength. Specimen 10A having been spoilt in machining the shear test was also omitted. In the case of rivets of a length of shank equal to $1·5d$ (30 millimetres) the tensile tests were not undertaken because the cylindrical portion of the test-pieces would have become too small to ensure the accuracy of the results.[2] The hardness of the A rivets of this size was therefore determined instead. In Table V., containing the results of the shrinkage measurements, the letters Z (tensile test), K (ball-pressure test), and S (shear test), placed against each rivet denote the respective test to which the rivet has been subjected.

The rivets of groups 1, 2, and 3 were removed whole from the plates. Otherwise the rivets used for tensile tests were removed by turning off the edge of the holding-up head, and the remainder by sawing off the holding-up head or by cutting the rivet throu hginthe centre.

[1] H. Moore, "Investigations on the Brinell Method of Determining Hardness"; *Proceedings of the International Association for Testing Materials*, 1909, vol. i. No. 9.

[2] Compare M. Rudeloff, "Contribution to the Study of the Appearance of Fracture of Tensile Test-bars." Interesting data are here given on the influence of shank length on the elastic limit, yield point, and appearance of fractures. See also Hütte, *Taschenbuch für Eisenhüttenleute*, 1910, p. 222.

TABLE II.—*Total Elongation of the Rivet, including the Head.*

Type of Rivet.	Load in Kilog.	Stress in Kilog. per Sq. Mm.		Length of Rivet Portion Examined. Mm.	Elongations of the Head End of the Rivet in Cms. $\times 10^{-5}$. Average Values of the Four Measuring Points under Load No.							Total Average λ_N Cm. $\times 10^{-5}$.
		In Shank.	In Screwed Part.		I.	II.	III.	IV.	V.	VI.	VII.	
Mild steel, 19 mm.	4500	16·4	23·9	128·6	989	989·5	990·0	988·0	988·5	988	...	988·8
Nickel steel, 23 mm.	9000	21·9	29·8	128·0	1340·0	1339·0	1339·0	1340·0	1340·0	1338·5	1339·0	1339·4

TABLE III.—*Determination of Elongation of Rivet Shank.*

Type of Rivet.		Dimensions of the Rivet at Different Sections. Distance from Top of Rivet Head in Cm.													Total.
		0·5	1·5	2·5	3·5	4·5	5·5	6·5	7·5	8·5	9·5	10·5	11·5	12·5	
Mild steel	Diameter, mm.	19·24	19·23	19·23	19·24	19·20	19·08	18·72	18·70	18·70	18·70	18·70	18·70	18·70	...
	Cross section, sq. mm.	290·7	290·4	290·4	290·7	289·5	279·4	275·2	274·6	274·6	274·6	274·6	274·6	274·6	...
	Length of interval, mm.	10·0	10·0	10·0	10·0	10·0	10·0	10·0	58·6						128·6
19 mm. diameter.	Elongation of the interval in cm. $\times 10^{-5}$ for E=20972 kilog. per sq. mm. P=4500 kilog.	73·80	73·88	73·88	73·80	74·11	76·79	77·96	457·81						982·03 $=\lambda_S$

Nickel steel .	Diameter, mm.	23·92	23·74	23·57	23·26	23·04	22·97	22·94	22·92	22·92	22·91	22·90	22·89	22·89	...
	Cross section, sq. mm.	449·4	442·6	436·3	424·9	416·9	414·4	413·3	412·6	412·6	412·6	411·9	410·7	410·7	...
	Length of interval, mm.	10·0	10·0	10·0	10·0	10·0	10·0	10·0	10·0	10·0	10·0	10·0	10·0	8·0	128·0
23 mm. diameter . .	Elongation of the interval in cm. $\times 10^{-5}$ for E = 20614 P = 9000 kilog.	97·16	98·64	100·06	102·75	104·72	105·36	105·64	105·82	105·82	105·91	106·00	190·97		1328·85 $= \lambda_S$

TABLE IV.—*Determination of Elongation of Rivet Head.*

Type of Rivet.	E = Kilog. per Sq. Mm.	Stress σ below the Head. Kilog. per Sq. Mm.	Elongation in Cm. $\times 10^{-5}$. Total Elongation Measured λ_N.	Shank Calculated λ_S.	Head $\lambda_K = \lambda_N - \lambda_S$.	Ideal Shank Length $l_1 = \left(\frac{\lambda_K \times E}{\sigma \times d}\right)d$. Single Rivet.	Mean.	Percentage of Error in the Calculated Rivet Stress when Heads are excluded. Length of Shank. $1·5d$.	$3d$.	$5d$.
Mild steel, 19 mm. diameter	20,972	15·5	988·8	982·0	6·8	$0·048d$	$0·047d$	6·3	3·1	1·9
Nickel steel, 23 mm. diameter	20,614	20·1	1339·4	1328·9	10·5	$0·045d$				

TABLE V.—*Results of Shrinkage Measurements.*

Rivet Group No.	Rivet Mark.	Particulars of Rivet. Length of Shank in $n.d$ Mm.	Method of Riveting.	Length of Riveting Time in Seconds (and Number of Strokes). Average Single Rivets.	Average for the Group.	Amount of Shrinkage $-\lambda$ mm. $\times 10^{-4}$ After Dividing the Test Pieces.	After Release of the Rivet.	Total Shrinkage.	Rivet Stress in Kg. per Sq. Mm. for E=21250 Kg. per Sq. Mm. $\sigma = \frac{\lambda E}{n.d}$		$\sigma^1 = \frac{\lambda . E}{d(n+2\times 0{\cdot}047)}$		Remarks. Z indicates tensile test. K ,, ball pressure test. S ,, shear test.
1	A	$1{\cdot}5d=$ 30 mm.	Hand Hammer	34 (?)	31 (?)	54	100	154	10·9	17·2	10·5	16·3	K
	B			30 (?)		156	108	264	18·7		17·6		K
	C			30 (?)		130	182	312	22·1		20·8		S
2	A		Pneumatic Hammer	12	12·6	108	104	212	15·0	17·8	14·2	16·8	K
	B			13		92	190	282	20·0		18·8		K
	C			13		64	198	262	18·5		17·4		S
3	A		Lever Press	3·5	2·7	10	374	384	27·2	26·9	25·6	25·3	K
	B			2·5		68	306	374	26·5		24·9		K
	C			2·0		80	300	380	26·9		25·3		S
4	A			**32 (?)**	**27 (?) Normal**	**52**	**512**	**564**	**20·0**	**18·1**	**19·4**	**17·6**	Z
	B			**27 (?)**		**10**	**640**	**650**	**23·0**		**22·3**		K
	C			**23 (?)**		**20**	**300**	**320**	**11·3**		**11·0**		S
5	A	...	Hand Hammer	20 (20)	24 (20)	82	600	682	24·2	25·1	23·4	24·3	Z
	B			25 (21)		8	680	688	24·4		23·6		K
	C			26 (20)		0	776	776	27·5		26·6		S
	6A			26 (20)		2	682	684	24·2		23·5		Z

6	B			31 (30)	32 (30)	24	850	874	31·0	28·8	30·0	27·9	K	
	C			33 (30)		0	750	750	26·6		25·7		Z	
8	A			8·4	8·3	38	644	682	24·1	25·8	23·4	25·0	Z	
	B			8·0		18	660	678	24·0		23·3		K	
	C			8·4		0	828	828	29·3		28·4		S	
7	A	3*d*	Pneumatic Hammer	10	10·7 Normal	2	824	826	29·3	29·4	28·3	28·5	Z	
	B			12		0	888	888	31·5		30·5		K	
	C			10		0	776	776	27·5		26·6		S	
9	A			15·4	15·1	36	746	782	27·7	29·0	26·8	28·1	Z	In the case of rivet 9C the punch mark on the rivet head was crushed in turning out the groove in the plate to release the rivet. The values obtained are therefore not sufficiently accurate to enable these to be included in striking an average.
	B			15·0		0	854	854	30·3		29·3		K	
	C			15·0		2	[662]	[664]	[23·5]		[22·8]		S	
10	A			3·0	2·5 Normal	36	869	905	32·1	30·2	31·1	29·3	—	
	B			2·0		60	750	810	23·7		27·8		K	
	C			2·5		34	810	844	29·9		28·9		Z	
11	A	...	Lever Press	5·0	5·3	44	876	920	32·6	32·2	31·6	31·1	Z	
	B			5·0		66	856	922	32·7		31·6		K	
	C			6·0		16	864	880	31·2		30·2		S	
12	A			7·6	7·6	2	946	948	33·6	32·4	32·5	31·4	Z	
	B			7·6		4	880	884	31·3		30·3		K	
	C			7·6		0	914	914	32·4		31·4		—	
13	A		Hand Hammer	38 (36)	37 (31)	34	1343	1377	29·3	28·3	28·8	27·8 (28·7)	Z	
	B			38 (32)		92	1345	1437	30·6		30·0 (32·7)		K	
	C			35 (26)		79	1097	1176	25·0		24·5		S	
14	A	5*d*	Pneumatic Hammer	17	15	39	1330	1369	29·1	28·7	28·6	28·2	Z	
	B			14		62	1317	1379	29·3		28·8		K	
	C			14		207	1099	1306	27·8		27·3		S	
15	A		Lever Press	3	2·3	247	1120	1367	29·1	28·1	28·5 (32·6)	27·5 (30·3)	Z	
	B			2		114	1230	1343	28·6		28·0 (32·1)		K	
	C			2		168	1083	1251	26·6		26·1		S	

III. RESULTS OF TESTS.

1. *The Rivet Stress.*

(*a*) *Elongation of the Head.*—In Table II. the values for the elongation are given which were obtained in determining the total elongation including the heads. They are noteworthy on account of the uniformity shown by the two rivets measured. In the case of the 19-millimetre rivet, in which the elongation was 1·2 centimetre $\times 10^{-5}$, the greatest variation from the mean amounted only to 0·21 per cent., and the 23-millimetre rivet, with an elongation of 0·9 centimetre $\times 10^{-5}$, differed only by 0·07 per cent. from the mean, which proved the accuracy of the measuring appliances. In Table III. the calculations for the elongation of the shank are given. The shank diameters recorded for the several intervals were measured with a micrometer screw, and the figures given represent the mean of every four measurements. The distance of the ring-marks on the shank from the under surface of the rivet head was determined on the Zeiss comparator and rounded off to the values given. In Table IV. the elongation of the head and the ideal shank length l_1 are entered, and the values for both rivets agree satisfactorily. In calculating the rivet stresses the mean of both values was taken. Table IV. also shows the errors in the calculation of the stresses due to neglecting the elongation of the head. Taking both heads into account, the amount of error in percentages of the shank length is:—

$$\frac{2 \times 0{\cdot}047}{n\,.\,d}\,100,$$

in which n, according to the specimens tested, equals 1·5, 3, and 5. Since the error in the case of rivets with a shank length equal to $5d$ amounts to 1·9 per cent., the more exact value of the stress, according to equation 5, is given for all rivets in Table V., as well as the calculation according to

equation 3. Fig. 9 illustrates how the curve of errors falls as the length of the shank increases.

(*b*) *Shrinkage of the Rivet.*—The values for the rivet shrinkage are entered in Table V., being arranged according to shank lengths and methods of riveting.

For calculating the stress within the rivet the mean modulus of elasticity, as found from the tensile tests on the driven rivets, was used, amounting in round figures to 21,250 kilogrammes per square millimetre. The values σ and σ^1 represent respectively the stress without and with taking into

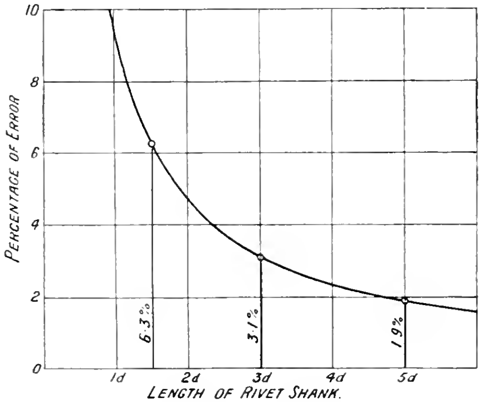


FIG. 9.—Error in Calculation of Stress, when Elongation of Rivet Head is neglected.

account the deformation of the head. From the three values of one rivet group the mean was also calculated each time. In groups 13, 14, and 15, with $l = 5d$, it was found, by measuring the shank diameters, that rivets 13B, 15A, and 15B had undergone a slight contraction of cross-section, and in these cases the equation

$$(4) \qquad \sigma^1 = \frac{\lambda \, . \, E}{l(n + 2\mu)}$$

no longer meets the conditions for calculating the tension on the rivet, because this equation applies only to bars of uniform section. Assuming now that the stress σ^1 is correct for the larger section F maximum under the snap-head, this then

is in inverse ratio to the stress σ_0 of the smallest section F minimum, that is:—

$$\sigma_0 = \sigma^1 \frac{\text{F max.}}{\text{F min.}}$$

In Fig. 38 the diameters of rivet 15A are given and the areas are:—

$$\text{F max.} = \frac{\pi \times 20^2}{4} = 314 \text{ sq. mm.}; \ \text{F min.} = \frac{\pi \times 18{\cdot}7^2}{4}$$
$$= 275 \text{ sq. mm.}$$

$$\text{Then } \sigma_0 = \frac{28{\cdot}5 \times 314}{275} = 32{\cdot}6 \text{ kgs. per sq. mm.},$$

a value which corresponds to a yield-point of 32·5 kilogrammes per square millimetre obtained for the same rivet under the tensile test (see Table VIII.). The corresponding stresses for rivets 13B and 15B work out at 32·7 and 32·1 kilogrammes per square millimetre respectively. These more exact values and their averages have been added in brackets in Table V. They have also been taken for plotting the curves in Fig 10, which show the relation between shank length and rivet stress for the three methods of riveting, and with normal lengths of riveting time.[1] From the curves, it is clear that, with all three methods of riveting, the stresses are lowest in the rivets with a shank length equal to 1·5*d*. For hand and pneumatic riveting they are nearly the same, namely, 16·3 and 16·8 kilogrammes per square millimetre, but in the case of press riveting the stress becomes much higher, up to 25·8 kilogrammes per square millimetre. With a length equal to 3*d* the stress on the hand-riveted rivets increases slightly, by 1·3 kilogramme per square millimetre, but the pneumatic riveting reaches a maximum stress of 28·5 kilogrammes per square millimetre, while the pressed rivets show a stress of 29·3 kilogrammes per square millimetre. With a shank length equal to 5*d* there is no difference between hand and pneumatic riveting, the stress in both cases averaging about 28·5 kilogrammes per square millimetre. The press

[1] All figures for groups 4, 7, and 10, with normal length of riveting time, are printed in heavy type.

riveting, however, showed a further increase up to 30·3 kilogrammes per square millimetre.

The length of riveting time shows its effect in all three methods, the stress being higher when the riveting time is longer. The averages for the various riveting times have been marked on the curves 17, 18, and 19, which show the influence of the time on the strength of the material. In the case of hand riveting, only the values corresponding to 20 and 30 hammer strokes are taken account of (groups 5 and 6).

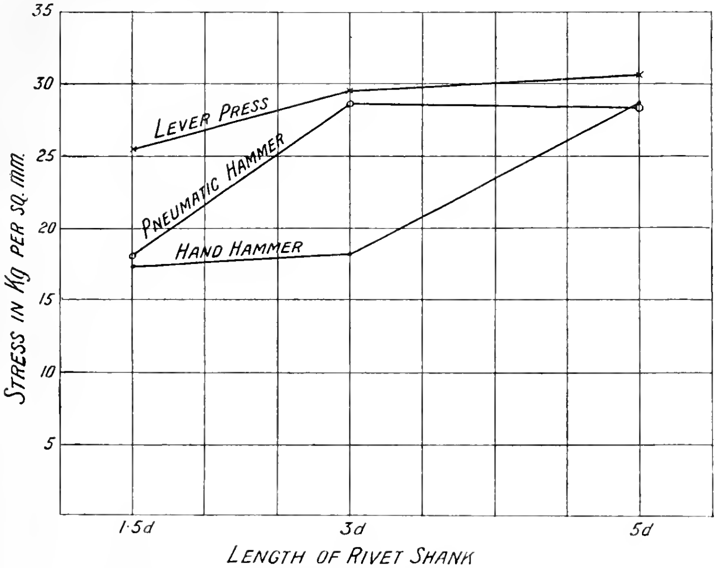


FIG. 10.—Influence of Length of Rivet Shank on the Rivet Stress.

The divergences of the single values from the average are also noteworthy in the case of the hand riveting with shank lengths of 1·5 and 3d, and normal riveting time (see groups 1 and 4, Table V.). Having regard to the fact that rivet 4C with a stress of only 11·3 kilogrammes per square millimetre was the one on which the shortest time was expended (23 seconds) as compared with 32 and 27 seconds spent on the other two rivets of group 4, it may be assumed that rivet 1A received fewer strokes, though a longer time was expended on it. In addition, a physiological effect comes into consideration here.

Rivet 1A was the first one to be put in and was driven just after the interval of a meal hour, so that the gang had not attained their full working speed. This is brought out more clearly by the rise in the values for rivets 1B and 1C. With the uniform number of 20 strokes on the rivets of group 5 and on rivet 6A, also in the case of 30 strokes on rivets 6B and 6C, the measured stresses are much more regular, especially in those rivets which received the 20 strokes. The increase in the stress produced by the additional 10 strokes amounted on the average to 7 per cent. of the stress found in rivets which received 20 strokes.

The pneumatic riveting of group 7, marked normal, showed greater uniformity of rivet stress than the normal hand riveting. This may be attributed to the fact that the speed of working of the compressed-air hammer is much greater and more uniform than in riveting by hand, the number of blows in a given time being approximately always the same. With rivets of shank length equal to $3d$, the normal time of 11 seconds expended in riveting appears to be the limit to which the time effect extends (compare group 7 with an average of 10·7 seconds). A longer time expended in work caused no increase in the stress. Rivet 9C was not taken account of in compiling the averages, as the measuring instrument was damaged in turning the layer out of one of the plates to loosen the rivet, and the record is therefore not trustworthy.

The press riveting showed by far the greatest degree of uniformity for rivets of all lengths. According to the average values of the stress plotted in Fig. 18 for a shank length equal to $3d$, the time effect does not appear to diminish until after 5·3 seconds. An examination of the single values for groups 10, 11, and 12, as shown in Fig. 11, shows, however, that a longer time than 3 seconds has scarcely any appreciable effect.

To find an explanation of the differences of rivet stress it is necessary to review the circumstances accompanying the origin of the stresses. The material of the finished rivet at the end of the riveting operation has a temperature of 500° to 600° C., the riveted plates having taken up heat from the rivet

body, which had originally a temperature of 900° to 950° C., causing them to expand. This condition is indicated by the point N in the diagram, Fig. 12, in which the origin of the stress is graphically represented. The work on the rivet then ceases and the joint begins gradually to cool. The rivet continues to give up heat to the air and plates and thereby tends to contract in length. If the plates were free to move, its reduction in length would probably proceed according to the curve marked "rivet (original)." The plates continue to absorb heat from the rivet and will at first expand. They then gradually return to the temperature of the atmosphere, cooling

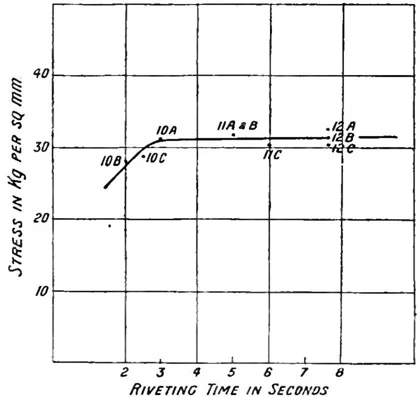


FIG. 11.—Influence of the Riveting Time on the Rivet Stress in Press Riveted Rivets. Single values for shank length $=3d$.

the rivet at the same time. The cooling curve for the plates shows the variation in the thickness of the plates according to the temperature of the rivet for the time being.[1] Since the length of the shank always corresponds to the thickness of the plates, tension must be set up in the rivet as it cools, and this tension at every stage in cooling is equal to the difference z of the ordinates of the corresponding superposed

[1] An initial thickening of the plates at the cessation of riveting, as drawn on the diagram, entails of course an increase in the length of the rivet. The effect of this on the position of the rivet cooling curves is that the ordinates up to the peak of the plate curve are to be laid off from the latter and, for the further cooling, from the tangent to the peak of the plate curve. In the diagram this reduced curve is drawn with a heavy line, the original one being shown by a dotted line.

points for the plate and rivet. By laying off this tension z from a straight line and by plotting along with it on the same scale the change in length of the shank corresponding to the yield point of the material for the same temperature, the curves Z and S are obtained. Since the ordinates below the yield point now represent the stress, the course of both curves shows the stress in the rivet at each stage of cooling,

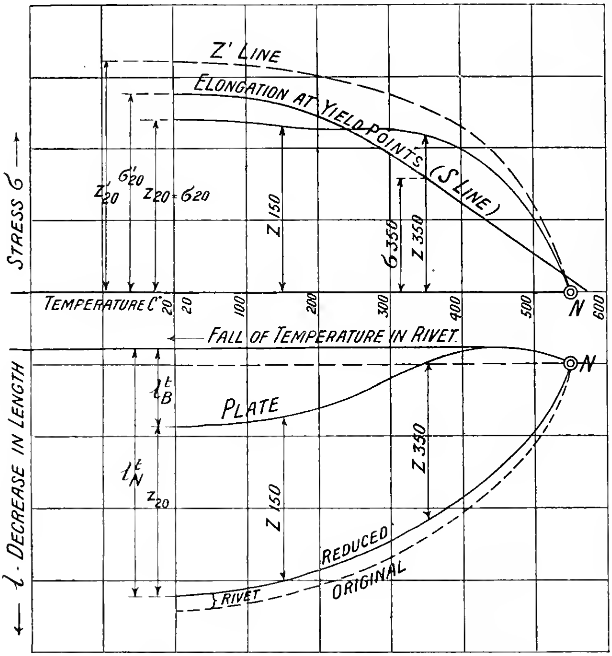


FIG. 12.—Origin of Stress within the Rivet.
(Graphic representation.)

the yield point forming the upper limit of the rivet stress. The point at which the tension line Z cuts the ordinate corresponding to the room temperature of 20° C. then gives the stress σ_{20} existing in the rivet when cold. With very great temperature differences it may happen that the Z line rises at all points above the S line, as indicated by the line Z^1. Then the S line represents at all points the stress within the rivet.

In the first place the diagram shows that apart from the yield point the difference in temperature between plate and rivet, as well as the relation of their coefficient of expansion, is of considerable influence on the magnitude of the stress. The greater the quantity of heat absorbed by the plate, that is, the greater the ordinate λ^t_B which represents the change of thickness of the plates while cooling, the smaller will be the value of the tension z_{20}. From this it may be concluded that in general a higher tension, and consequently a greater stress, is produced in thin rivets than in thicker ones, for the reason that the latter give up more heat to the plate up to the end of riveting. On the one hand, more heat units are stored up, and, on the other, the surface of contact between plate and rivet is larger. If the coefficient of expansion of the rivet exceeds that of the plate, it will tend to enlarge the distance λ^t_N, that is, $z_{20} = \lambda^t_N - \lambda^t_B$, and thereby to increase the stress. In the reverse case a lower coefficient of expansion within the rivet will result in a small λ^t_N, that is, a low value for z_{20} and a low stress. Such cases occur with certain nickel and chromium-nickel alloys. Frémont,[1] for instance, found that in riveted joints made of these special steels, with a yield point up to 60 kilogrammes per square millimetre there was little or no resistance to slip. This phenomenon is due to the fact that the critical points of such alloys usually lie very low and are accompanied by peculiar changes (reductions) in the coefficient of expansion. The causes of the differences in stress in rivets of various lengths and in different systems of riveting may be summarised as follows:—

Short rivets always show lower stresses than longer ones, because with the short ones more heat in proportion to the length escapes through the heads and the tools in contact therewith. The speed with which the snap-head is formed plays an important part in the riveting process, because the stresses are set up in the rivet immediately the head is finished. If finished quickly, the temperature of the shank is still very high, λ^t_N becomes very great, and the difference in temperature between the rivet and the plates is greater, so that the distance

[1] Frémont, "De la Résistance des Pièces rivées"; *Bulletin de la Société d'Encouragement*, 1909, vol. i. p. 675.

z_{20} becomes very large. At slower riveting speed λ^t_N becomes smaller, and the difference z_{20} is less compared with the expansion of the plate.

With very long rivets the speed of forming the head, and therefore the different systems of riveting, cease to have much effect because the loss of heat through the head is not great in comparison with the length, and a considerable part of the shank remains for some time at a higher temperature. With long rivets, therefore, the condition represented by the Z^1 line may easily occur.

From the foregoing it is easy to see why the highest stresses occur with the press, which closes the rivets at great speed. A prolongation of the riveting time also has little effect. Next lower in order of magnitude come the stresses in the rivets driven with the pneumatic hammer, and finally those in the hand-driven rivets. In the case of very short rivets of $1{\cdot}5d$ the effect of the loss of heat in hand and pneumatic riveting is very noticeable. In the rivet with length equal to $3d$ the lower stresses in the hand riveting are due to the method of forming the head, which, in consequence of the weak beading over of the fibres of the material, tends to cause the head to be drawn into the rivet hole (see photograph Fig. 39). To a less extent the same thing is apparent in the pneumatic riveting. In both cases it is noticeable that the better the head is beaded over the higher the stress in the rivet. In very long rivets, however, these circumstances have no further influence. This is manifest from the fact that in the hand-driven and in the pressed rivets with a length $= 5d$ the stresses were found to coincide with the yield point of the material, so that here again the condition occurred as represented by the Z_1 line in Fig. 12.

Apparently the yield point has an influence on the stress even when it has not nearly been reached. This is shown by the diagrams for the yield point and rivet stress for the pneumatic and press riveting (see Figs. 17 and 18). For rivets of a length $= 3d$, the change in the riveting time from the first time scale to the second has produced an increase in the yield point and stress. With the pneumatic riveting the lines run almost parallel. In press riveting it is possible, by

using high-grade material with a high yield point, to raise the stresses in the rivets, confirmation of which is afforded by Frémont's[1] experiments in which he noted the increased resistance to slip. Assuming uniform differences of temperature between rivet and plate and normal cooling conditions, this increase of stress depends very much upon the magnitude of the coefficients of expansion of both rivet and plate or on the mutual relation of these. In any case, with short rivets the high yield point of special material can never be utilised to the full, at least as far as hand and pneumatic riveting are concerned.

The results of the stress measurement in pressed rivets correspond practically with the values found by Bach and Baumann,[2] who also found lower stresses in short rivets than in long ones, and that the time during which the press was applied exercised no appreciable influence provided the plates were smooth and close fitting. With regard to the time effect, however, it should be noted that their conditions did not correspond exactly with ordinary practice, since full pressure was reached only after 10 to 15 seconds. The small routine investigation alluded to by the author in the Introduction was made on sets of three rivets, each set being uniformly driven in a prescribed manner by hand, pneumatic hammer, and toggle lever press respectively. The shank diameter was 26 millimetres, and the length 42 millimetres or $= 1{\cdot}6d$ approximately. For the hand and pneumatic riveting the stress averaged about 15 kilogrammes per square millimetre, and for the press riveting 24 kilogrammes per square millimetre, which agree well with the values found in the present research.

It may here be mentioned that the superficial pressure on the head, 30 millimetres diameter, was

$$p = \frac{55000}{\pi \frac{30^2}{4}} = \text{about 78 kilogrammes per square millimetre,}$$

but in spite of this heavy pressure in comparison to the rivet cross section no injury was done to the surface of the plate, which perhaps is due to the short time the pressure was

[1] *Ante.* [2] *Ante.*

applied and the wide edge of the closing die, which formed a strong fin round the base of the rivet head.

2. *Strength Properties of the Material used and of the Driven Rivets* (Plates XI. to XIII.).

(*a*) *Raw Material.*—The results of the tensile tests with raw material are given in Plates XI. and XII. Tests 8 to 11 show satisfactory agreement throughout. The material has the usual properties of good mild steel with an average yield point of 26·6 and breaking strength 37·1 kilogrammes per square millimetre. Elongation was 31·4 and contraction of area 67·2 per cent. Bar 8, taken from the end of an unused rivet and previously annealed at 900° C. for half an hour, shows a somewhat higher yield point, and consequently also a higher value for the ratio $\frac{\sigma_S}{\sigma_B}$, but it was included for the purpose of obtaining the mean results, since the material of the round rod and of the unused rivets, both in the annealed condition, showed the same ball pressure hardness, averaging 83·4 kilogrammes per square millimetre. The shearing resistance of the round rod, not annealed, is 31·2 kilogrammes per square millimetre, and its ball pressure hardness was 90·4 kilogrammes per square millimetre, which is also normal (see Plate XII.). On the other hand, tests 1 to 7 call for some observations, and the method of preparing the test-piece shown in Fig. 7 should be examined in this connection. In tests 1 and 2, which were performed for purposes of comparison with tests 9 to 11, the remarkable fact occurred that both rivets broke towards the holding-up head close to where the division marks ended and showed hardly any elongation. Bar No. 1 showed none at all in a length of 70 millimetres towards the end of the shank, but at the same time the yield point and the tensile strength were distinctly higher than in tests 9 to 11. Other bars, Nos. 3, 4, 6, and 7, were taken, one pair from one rivet, and of these Nos. 3 and 4 from the end near the head had a somewhat lower yield point and breaking strength and a correspondingly higher elongation, though the point of fracture had the same relative position to the

holding-up head of the rivet from which the bars were taken, as in tests 1 and 2. The higher values for these may be due to the fracture taking place close to the head, so that elongation was hindered at one end. The bars 6 and 7 from the shank end, on the other hand, broke in the middle and showed a very considerable increase in the yield point and breaking

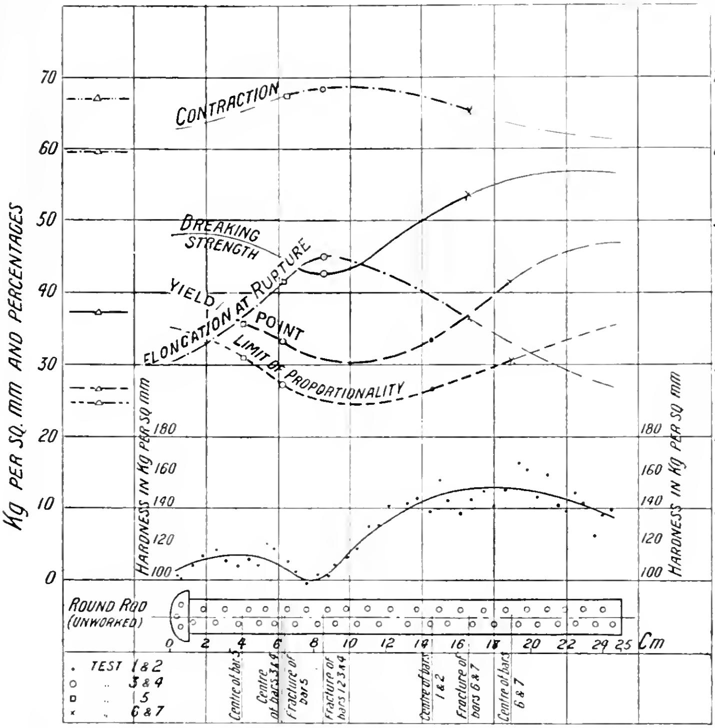


FIG. 13.—Variations of Tensile Properties due to Stamping of Holding-up Head.

strength. In particular, it is noteworthy that the breaking strength of bar 6 rose to 59·6 kilogrammes per square millimetre. Specimen 5, taken from a piece of the head end left over, shows a slight increase in the yield point and breaking strength as compared with tests 1 to 4. From the values found the curves in Fig. 13 have been plotted in the following manner. The values for the limit of proportionality and the yield point were plotted as the abscissæ of the rivet (corres-

ponding with the centre of the test bar) represented underneath the curve, for the reason that these values were measured with apparatus adjusted symmetrically with the centre of the bar. The values for breaking strength, elongation, and contraction, on the other hand, were plotted according to the position of the point of fracture. The curves show clearly that the rivet shanks at a distance of about 8 centimetres from the top of the head have a minimum of strength and a corresponding maximum elongation. A hardness test performed on a similar rivet confirmed this well, and the hardness curve shows a surprising agreement with the results of the tensile tests. For the sake of clearness that part of the curves corresponding with the latter has been drawn in more heavily. On the left the corresponding average values determined by tests 8 to 11 for the raw material are given for comparison. For readier reference the points of fracture and position of centres of bars in the rivet shank have been marked, and the values obtained in the individual tests are indicated by points.

It was observable from the nature of the surface of the rivets that in their manufacture the effect of the heating necessary for forming the head had extended to a distance of about 100 millimetres, measuring from the top of the head. In the process of stamping the head a compression of the material had taken place, extending into the shank, as similarly occurred in the pressed rivets, in which, in the case of rivets of length $= 1{\cdot}5d$ and $3d$, the hardness increases from the riveted head to the holding-up head. As the curve shows, the average hardness at the hardest spot is 152 kilogrammes per square millimetre, and this considerable increase in hardness in the end of the shank is due to cold working. The effect of compression was in fact clearly visible on the sections from the ends of the shanks.

The results of the tests at high temperatures are also given in Table VI., Plate XI., under Nos. 6–17. These tests were intended to throw light on the behaviour of the material in cooling, but in order to approximate to actual conditions, the material ought properly to have been heated in the laboratory furnace to about 900° C. and the test performed at the desired temperature range. Such a method of procedure is, however, not

practicable in view of the fine measurements to be made. Before testing, the bars were therefore annealed for 20 minutes at 900° C. and slowly cooled in dry sand. The test was then performed at the desired temperature,[1] and the values entered in Fig. 14 have circles drawn round them to distinguish

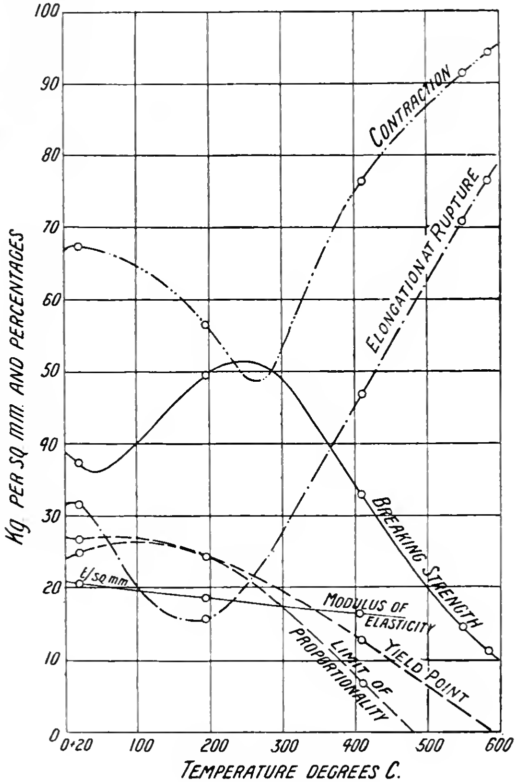


FIG. 14.—Influence of Temperature on the Tensile Properties of the Rivet Material.

them. The method of plotting the curves follows that adopted by Martens[2] for recording the results of the tests. In apply-

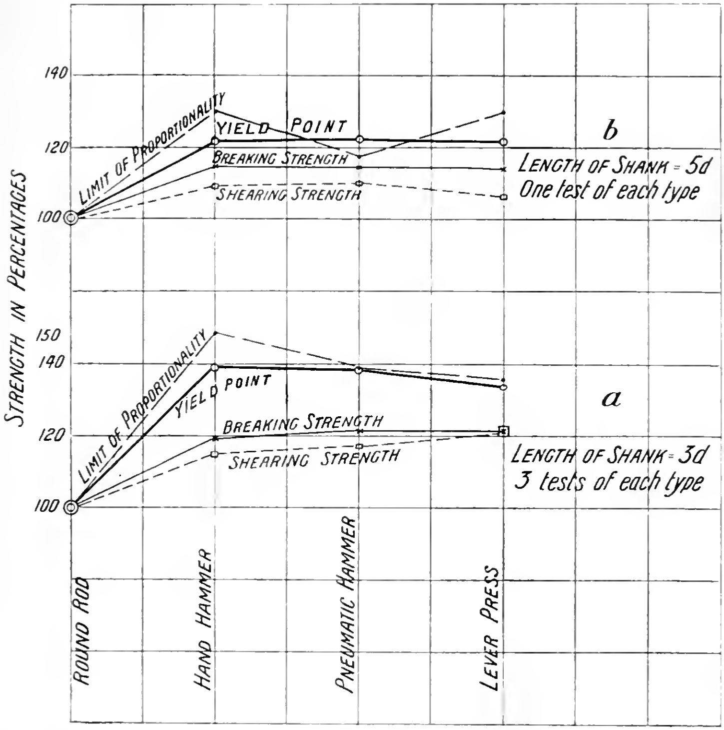
[1] By annealing, the effect of stamping the head, described above, was entirely removed from the test bars taken from the unused rivets, as is shown by the values obtained for test No. 8. Fracture also occurred in the centre of the bar.

[2] Martens, "Untersuchungen über den Einfluss der Wärme auf die Festigkeitseigenschaften des Eisens"; *Mitt. aus den Königl. Techn. Versuchsanstalten*, 1890, No. 4, pp. 159–214. For comparison hardness range, No. 1 was used.

ing the results to the object in view account has to be taken of the circumstance, to be more fully explained later, that the strength of the material is increased by riveting, so that naturally the figures obtained do not agree exactly with those for the driven rivet. But the dimensions of the testing apparatus did not permit of testing a specimen from the driven rivets. From the curve of the yield point it may be seen that this rises slowly from about the temperature at which work on the rivet ceases, until it reaches its maximum at room temperature. The breaking strength, in contrast, shows a very considerable increase between 200° and 300° C. as compared with the breaking strength at room temperature.

(*b*) *Finished Rivets.*—Tables VIII. and IX. (Plates XII. and XIII.) give the results of tensile and shear tests with the material of the driven rivets. To facilitate comparison, the corresponding average values obtained from tests 8 to 11 on raw material are entered in the top line. In the last column of Table VIII. comparative figures are given for rivet strength and raw material, the former being expressed in percentages of the latter. In the diagram, Fig. 15, *a* and *b*, is shown the influence of the riveting methods on the strength of the material, in the case of rivets of length $= 3d$ and $5d$. The values plotted are those shown in the last column of Table VIII. All the methods produce a considerable increase of strength as compared with the properties of the round rod, the amount of increase being about double as great for rivets $= 3d$, as for those equal to $5d$. The influence of the particular methods is also noticeable in rivets $= 3d$ (see curves of group A, Fig. 15). The yield point is highest in the hand-riveted rivets, the increase being higher here than in the pressed rivets and pneumatic rivets by 5·3 per cent. and 1 per cent., respectively, of the yield point of the raw material. This appears to be due to the shorter riveting time of the press, the essential riveting operation being complete at a higher temperature than in the other two methods. A slight influence of the time, and therefore of the temperature, is also noticeable as between hand riveting and pneumatic riveting. Since the breaking strength is not raised in the same proportion as the

yield point, the ratio $\frac{\sigma s}{\sigma_B}$ is considerably increased. In the hand riveting it rose on an average from 71·8 to 83·7 per cent., whereas in the pneumatic and press riveting it only rose to 78·2 and 79·1 per cent. In contrast to the increase in the yield point, upon which the magnitude of the stress in the



FIGS. 15 (*a*) and 15 (*b*).—Influence of Method of Riveting and Shank Length on the Strength of the Rivet.

rivet so much depends, the increase in the shearing strength is not nearly so great, and it is always less than the rise in the breaking strength. The press riveting showed the highest increase in the shearing strength, rising to 6 per cent. more than in the hand rivets, while the pneumatic riveting comes about halfway between. Moreover, it is remarkable that in the hand riveting the limit of proportionality coincides every-

where with the yield point, that is, it undergoes the greatest increase as compared with its value in the raw material. From Fig. 15 it will be seen that the strength increments for rivets of length $= 5d$ are smaller than for length $= 3d$, but are in general more uniform with regard to the three riveting methods. In the rivet with length $= 5d$ the shearing strength is less in the press rivets, and the value of the limit of proportionality is, perhaps accidentally, very much lower

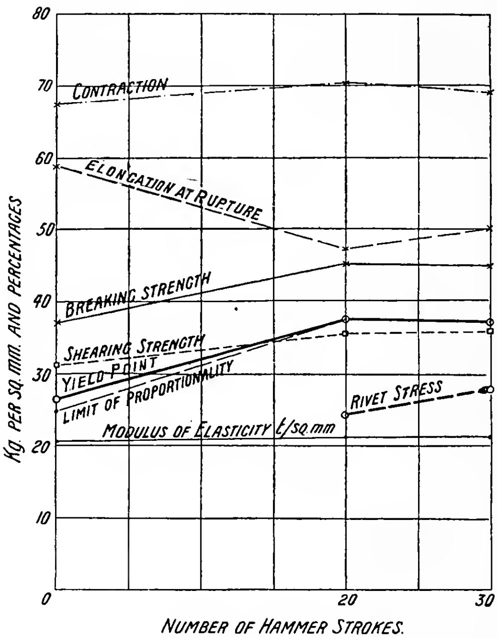


FIG. 16.—Influence of Riveting Time in Hand Riveting.

in the pneumatic riveting. The tensile test on the pressed rivets of group 15 show a lower ultimate elongation, which is due to the fact that in the centre of the rivet there was a hard spot which did not stretch equally with the rest of the material. Finally, the modulus of elasticity was increased for all rivets, namely, by 3·5 per cent. for length $= 3d$ and 2·7 per cent. for length $= 5d$.

The influence of the riveting time is shown by means of curves in Figs. 16, 17, and 18. For the sake of clearness, in

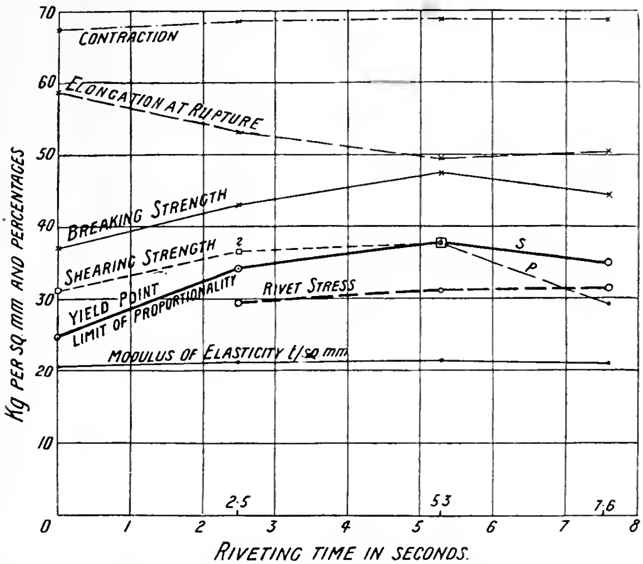


FIG. 17.—Influence of Riveting Time in Pneumatic Hammer Riveting.

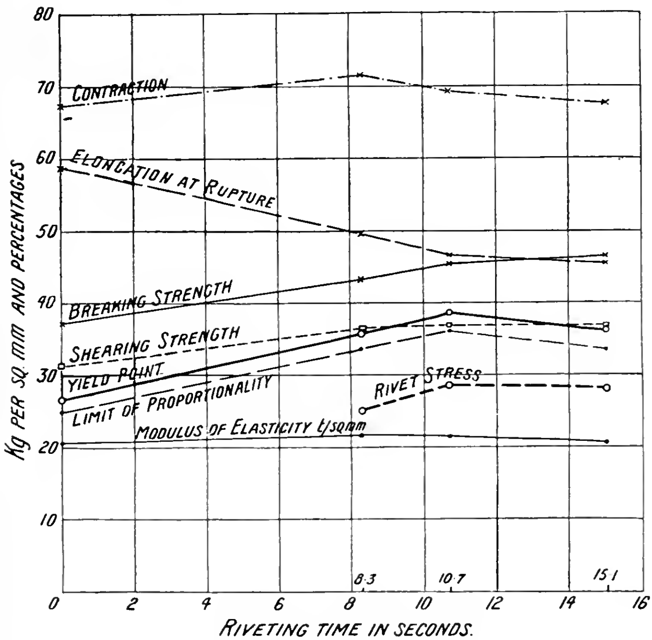


FIG. 18.—Influence of Riveting Time in Press Riveting.

plotting the values the mean riveting time or number of hammer strokes, as the case may be, of the group in question were taken as abscissæ for all values. The starting points in each case are the average values for the round rod laid off on the axis of the ordinates. For the hand riveting only the figures for groups 5 and 6 are given, which received 20 and 30 strokes respectively. The agreement is excellent between the values obtained with specimens 5A and 6A each with 20 strokes (see Table VIII.), the means of which were used for the curve. A longer riveting time produced an increase in the strength in the case of pneumatic and pressed rivets, but not in that of hand riveting. On prolonging the operations beyond the second time-scale a slight reduction in the strength occurred, with the exception of the breaking strength in the pneumatic riveting, which underwent a further small increase. In Figs. 16 to 18 the curves for the average values of the rivet stresses are also drawn. In the case of the pneumatic hammer and toggle lever press, the rise in the stresses with increasing yield point from the first to the second time-scale is plainly noticeable. In the pneumatic riveting this is remarkable in that the yield point for both time-scales is about 10 kilogrammes per square millimetre higher than the measured stresses in the rivets, a point already alluded to in discussing the latter.

The results of the hardness tests for the rivets of different length are plotted in Figs. 19 to 37. The respective hardness numbers are noted against the circles representing the position of the impressions. The increase in the strength of the material throughout is accompanied by an increase in the ball pressure hardness, which averages about 30 to 35 kilogrammes per square millimetre as compared with the hardness of 83·4 kilogrammes per square millimetre of the annealed material, equivalent to an increase of about 40 per cent. With a shank $= 3d$ the influence of the riveting method is most clearly marked, but the difference lies not so much in the varying magnitudes of the hardness numbers as in the effects produced by the different methods of closing the head. In both methods of riveting by hammer the hardness diminishes towards the holding-up end, which is shown on

TABLE VI.—*Strength Properties of the Material Employed.* (a) *Tensile Tests.*

Test No.	Test Bar taken from	Dimensions of Test Bar in Millimetres. Diameter.	Dimensions of Test Bar in Millimetres. Measured Length.	Condition of Material.	Tested at Temperature. Degrees C.	E Modulus of Elasticity in Kilogrammes per Square Millimetre. Single Values.	E Mean.	Stresses in Kilogrammes per Square Millimetre. σ_P Limit of Proportionality. Single Values.	σ_P Mean.	σ_S Elastic Limit. Single Values.	σ_S Mean.	σ_B Breaking Strength. Single Values.	σ_B Mean.	Ratios in Percentages. $\frac{\sigma_P}{\sigma_B}$ Single Values.	$\frac{\sigma_P}{\sigma_B}$ Mean.	$\frac{\sigma_S}{\sigma_B}$ Single Values.	$\frac{\sigma_S}{\sigma_B}$ Mean.	Elongation δ in Percentages of $2\cdot26\sqrt{f}$. Single Values.	$2\cdot26\sqrt{f}$ Mean.	$5\cdot65\sqrt{f}$ Single Values.	$5\cdot65\sqrt{f}$ Mean.	$11\cdot3\sqrt{f}$ Single Values.	$11\cdot3\sqrt{f}$ Mean.	Contraction of Area, per Cent. Single Values.	Contraction Mean.
1	Rivet shanks, Fig. 1. From plain end of shank.	14	140	As delivered.	20 (Room temperature).	21,000	20,850	27·7	26·7	31·1	33·5	42·7	43·8	62·7	60·0	72·9	76·4	46·5	44·7	20·6	20·3	10·3	9·9	64·9	64·3
2						20,700		25·6		35·8		44·8		57·2		79·9		42·9		20·0		9·5		63·6	
3	From head end.		70			20,910	20,755	28·8	27·3	31·4	33·1	41·0	41·5	70·3	65·3	76·6	79·7	46·9	45·3	24·3	23·5	...	...	68·0	68·2
4						20,600		25·7		34·7		42·0		61·2		82·8		43·6		22·6		...		68·4	
5			42			20,910		30·9		35·7		44·4		69·7		8 4		41·1		...		...		67·3	
6	From plain end of shank.		70			20,910	20,925	35·2	30·4	44·9	41·4	59·6	53·9	59·1	56·2	75·4	77·0	34·7	36·5	22·7	23·2	...	...	58·9	65·2
7						20,940		25·6		37·8		48·2		53·2		78·5		38·2		23·7		...		71·3	
8			140	Annealed.		20,350	20,510	28·2	24·9	28·2	26·6	36·8	37·1	76·7	67·1	76·7	71·8	62·9	58·9	40·8	39·8	30·9	31·4	68·7	67·2
9	Round rod. Fig. 1.	18·8	200	As delivered.		20,750		24·5		24·5		36·4		67·4		67·4		59·2		41·4		34·6		66·6	
10		14	140			20,700		23·4		27·3		37·8		61·9		72·3		57·9		39·7		30·9		64·8	
11		10	100			20,250		23·3		26·5		37·5		62·2		70·8		55·5		37·4		29·1		68·8	
12	Round rod.	10	100	Annealed.	...	18,600	18,600	24·5	24·2	24·5	24·2	50·0	49·4	49·0	49·0	49·0	49·0	...	...	21·2	20·1	17·0	15·8	55·1	56·5
13	Plain end of rivet shank.					18,600		23·9		23·9		48·8		49·0		49·0		...		19·0		14·5		57·8	
14	Round rod.				...	17,750	16,375	7·0	12·7	13·0	12·7	34·4	33·0	20·4	20·9	37·8	38·2	...	...	57·8	62·0	48·3	46·9	75·0	76·3
15	Plain end of rivet shank.					15,000		6·8		12·4		31·7		21·4		38·5		...		66·2		45·5		77·5	
16					...	...		...		...		14·5		...		...		...		...		71·0		91·3	
17	Round rod.				...	...		...		...		11·1		...		...		...		...		75·0		94·3	

TABLE VII.—*Strength Properties of the Material Employed.*
(b) *Shear Tests.*

Test No.	Test Bar taken from	Diameter. Millimetres.	Resistance of Shear τ in Kilogrammes per Square Millimetre.		Ratio $\frac{\sigma}{\sigma_B}$ in Percentages.	
			Single Values.	Mean.	Single Values.	Mean.
1			32·0		86·3	
2	Round rod.	13	30·9	31·2	83·4	84·3
3			30·8		83·1	

TABLE IX.—*Shearing Strength in Rivets of* $l = 1{\cdot}5d$.

Rivet Group No.	Riveting Method.	Riveting Time in Seconds (Average.)	Shearing Strength.	
			Kg. per Sq. Mm.	In Percentages of the Round Bar.
1	Hand hammer . .	31·0	33·9	108·6
2	Pneumatic hammer	12·6	34·6	110·9
3	Lever press . . .	2·7	35·4	113·5

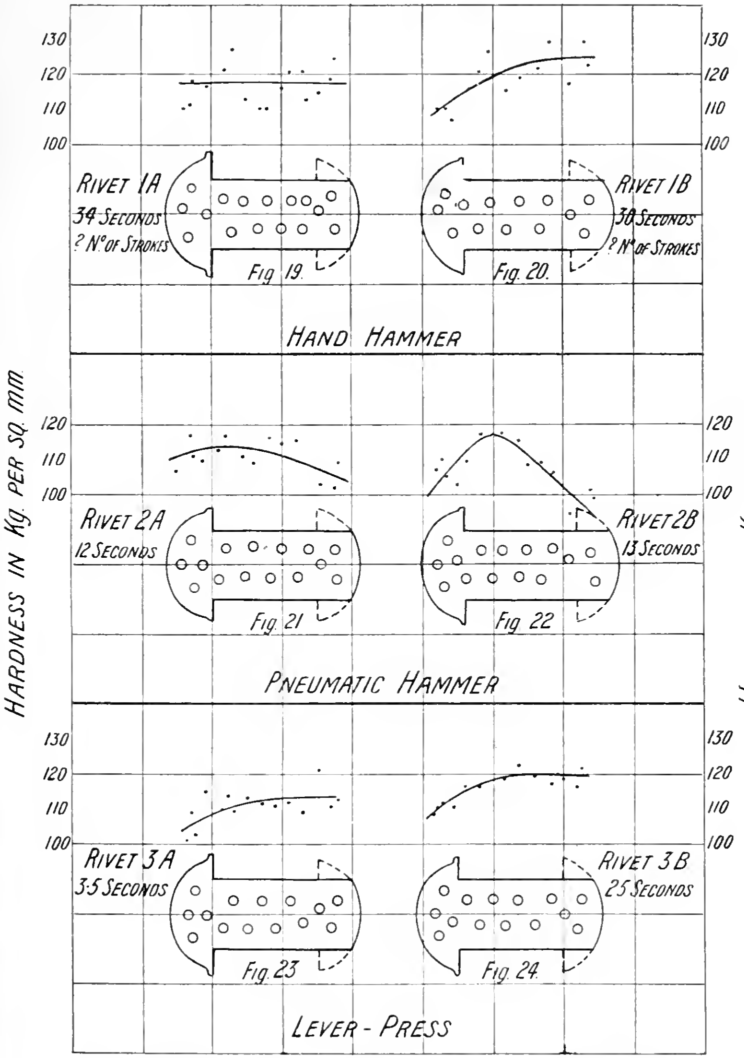
TABLE VIII.—*Strength Properties of the Driven Ri*

Rivet Group No.	Particulars of Rivet Group. Method of Riveting.	Riveting Time in Seconds (Average Number of Strokes).	Length of Shank.	E Modulus of Elasticity in Kilogrammes per Square Millimetre. Single Values.	E Mean.	Stresses in Kilogrammes per Square Millimetre. σ_P Single Values.	σ_P Mean.	σ_S Single Values.	σ_S Mean.	σ_B Single Values.	σ_B Mean.	τ Single Values.	τ Mean.	Elongation δ in Percentages. $2{\cdot}26\sqrt{f}$ Single Values.	$2{\cdot}26\sqrt{f}$ Mean.	$5{\cdot}65\sqrt{f}$ Single Values.	Contraction of Area, per Cent. Single Values.	Contraction Mean.	Ratios in Percentages. $\frac{\sigma_P}{\sigma_B}$ Single Values.	$\frac{\sigma_P}{\sigma_B}$ Mean.	$\frac{\sigma_S}{\sigma_B}$ Single Values.	$\frac{\sigma_S}{\sigma_B}$ Mean.
Properties of the raw material (see Table VI.), mean of tests 8, 9, 10, 11.				20,510		24·9		26·6		37·1		31·2		58·9		39·8	67·2		67·1		71·8	
4		**27 (?)**		**21,230**		**35.7**		**35·7**		**41·8**		**35·9**		**42·0**		...	**68·8**		**85·4**		**85·4**	
5	Hand hammer	24 (20)	3*d*	21,210	21,230	37·4	37·1	37·4	37·1	45·7	44·3	35·8	35·9	50·7	46·8	...	71·4	69·5	82·0	83·7	82·0	83·7
(6A)				21,210		37·8		37·8		44·8				44·0		...	68·8		84·4		84·4	
6		32 (30)		21,260		37·3		37·3		45·0		...		50·4		...	69·1		83·0		83·0	
13		37 (31)	5*d*	21,080		32·4		32·4		42·5		34·2		53·6		30·6	70·6		76·4		76·4	
8		8·3		21,600		33·7		35·7		43·2		36·4		49·4		...	71·5		78·0		82·7	
7	Pneumatic hammer	**10·7**	3*d*	**21,350**	21,280	**36·2**	34·5	**38·7**	36·8	**45·4**	45·0	**36·8**	36·7	**46·3**	47·1	...	**69·1**	69·8	**68·8**	73·1	**74·3**	78·2
9		15·1		20,910		33·7		36·1		46·5		36·8		45·7		...	68·8		72·5		77·6	
14		15	5*d*	21,020		29·2		32·5		42·5		34·3		56·1		32·9	70·6		68·8		76·5	
10		**2·5**		**21,200**		**34·1**		**34·1**		**43·2**		**...**		**53·0**		...	**68·7**		**79·0**		**79·0**	
11	Lever press	5·3	3*d*	21,450	21,230	37·8	33·7	37·8	35·6	47·6	45·1	37·8	[37·8]	49·7	51·0	...	68·8	68·8	79·5	74·7	79·5	79·1
12		7·6		21,190		29·2		**35·0**		44·5		...		50·3		...	68·8		65·6		78·7	
15		2·3	5*d*	21,080		32·3		32·3		42·3		33·1		51·2		30·7	70·5		76·5		76·5	

BLE VIII.—*Strength Properties of the Driven Rivet.*

entages.	Contraction of Area, per Cent.		Ratios in Percentages.						Properties of the Driven Rivets in Percentages of the Strength of the Raw Material.													
$5{\cdot}65\sqrt{f}$			σ_P/σ_B		σ_S/σ_B		τ/σ_B		E		σ_P		σ_S		σ_B		τ		δ $2{\cdot}26\sqrt{f}$		Contraction of Area, per Cent.	
Single Values.	Single Values.	Mean.	Single Values.	Mean.	Single Values.	Mean.	Single Values.	Mean.	Single Values.	Mean.	Single Values.	Mean.	Single Values.	Mean.	Single Values.	Mean.	Single Values.	Mean.	Single Values.	Mean.	Single Values.	Mean.
39·8	67·2		67·1		71·8		84·3		100		100		100		100		100		100		100	
...	68·8		85·4		85·4		85·9		103·5		143·3		134·1		112·6		115·0		71·3		102·0	
...	71·4	69·5	82·0	83·7	82·0	83·7	79·0	82·5	103·4	103·5	150·3	148·8	140·5	139·2	123·0	119·4	114·8	114·9	86·0	79·4	105·9	103·1
...	68·8		81·0		81·4				103·4		151·8		142·0		120·7				74·7		102·0	
...	69·1		83·0		83·0		...		103·7		149·8		140·3		121·3		...		85·7		102·6	
30·6	70·6		76·1		76·4		80·5		102·8		130·0		121·7		114·4		109·6		91·1		105·0	
...	71·5		78·0		82·7		81·4		105·3		135·3		134·1		116·4		116·6		83·9		106·0	
...	69·1	69·8	68·8	73·1	74·3	78·2	81·1	80·6	104·0	103·7	145·4	138·7	145·3	138·3	122·3	121·3	118·0	117·5	78·6	80·0	102·5	103.5
...	68·8		72·5		77·6		79·2		101·9		135·3		135·6		125·3		118·0		77·5		102·0	
32·9	70·6		68·8		76·5		80·7		102·5		117·2		122·2		114·4		110·0		95·3		105·0	
...	68·7		79·0		79·0		...		103·4		137·0		128·1		116·4		...		90·0		101·9	
...	68·8	68·8	79·5	74·7	79·5	79·1	79·5	[79·5]	104·6	103·7	151·8	135·4	142·0	133·9	128·2	121·5	121·1	[121·1]	84·3	86·8	102·0	102·0
...	68·8		65·6		78·7		...		103·2		117·3		131·6		119·9		...		85·4		102·0	
30·7	70·5		76·5		76·5		78·4		102·8		129·6		121·3		114·0		106·1		86·9		104·9	

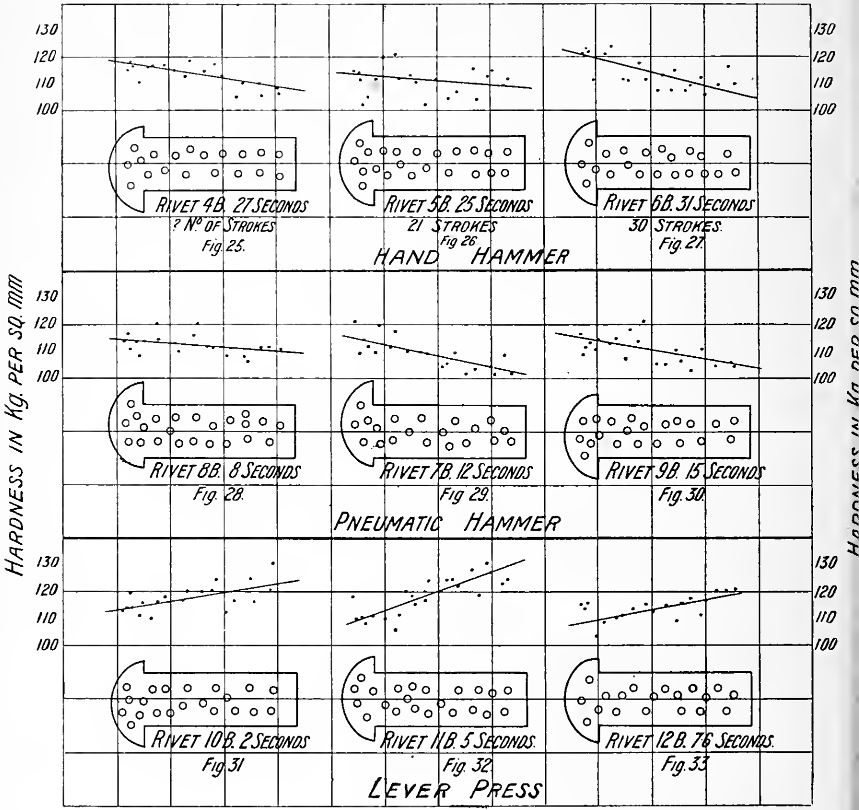
the right in all the illustrations. The material is gradually



FIGS. 19–24.—Influence of Riveting on the Hardness of the Material. Length of Shank $=1{\cdot}5d$.

pressed towards that end, but the direct influence of the blow does not extend as far as the holding-up end. In the press

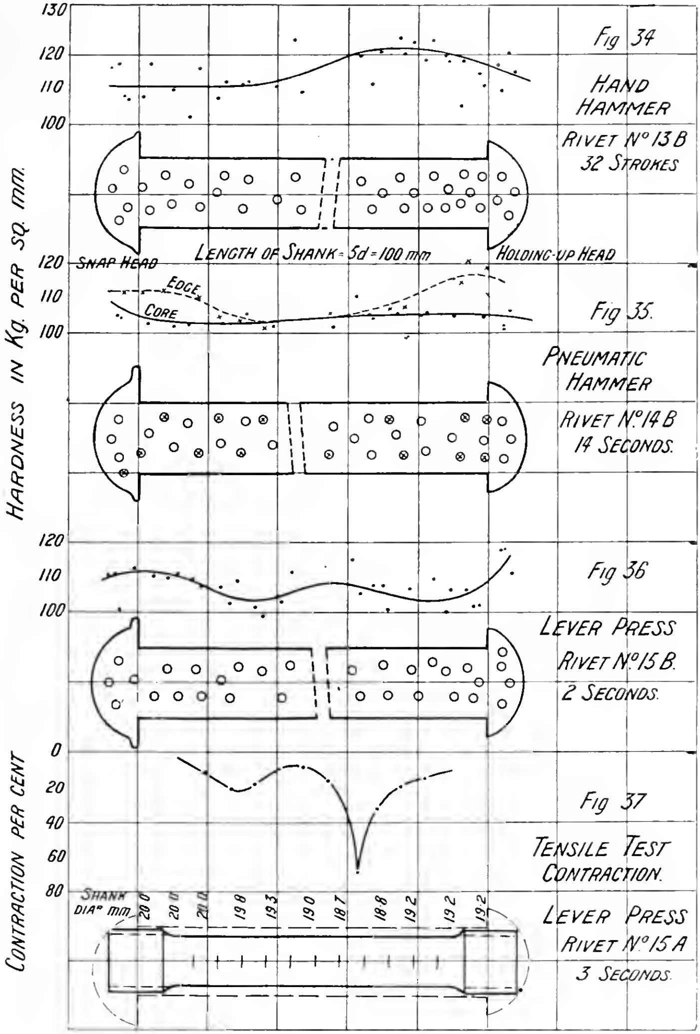
riveting the contrary is the case, but the crushing effect extends throughout the whole length of the rivet owing to the pressing back of the shank material at first upon the holding-up head. Since there is no room for the metal to



FIGS. 25–33.—Influence of Riveting Time on the Hardness of the Rivet Material. Shank Length $=3d$.

escape at that end, the greatest compression of the material takes place there. In conformity with this effect, the pressed rivets filled the holes in the plates more tightly just under the holding-up head than the hammer driven rivets, in which the swelling due to hammering down extended only through one-half to two-thirds of their length, at least in the case of

those with length $=3d$. In these rivets the position of the



FIGS. 34–37.—Influence of Riveting on the Hardness of the Material. Length of Shank $=5d$.

point of fracture in the tensile tests confirmed the decline in hardness. In all the pressed rivets fracture occurred in the

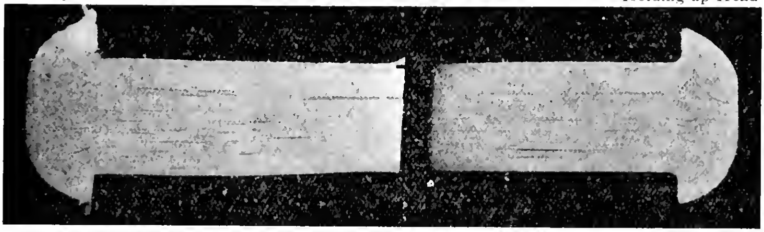
half of the test bar under the snap-head, whereas in the hand and pneumatic driven rivets it occurred between the centre and the holding-up head. With regard to the influence of the riveting time, the hardness tests confirmed the results of the corresponding tensile tests on the pneumatic and press riveting in showing that the time effect ceases at the second time scale. In the hand riveting, the rivet which received 30 hammer strokes showed the highest value for hardness. The respective positions of the lines representing the mean hardness results for the press riveting and hammer riveting show that, on an average, the value of the former is about 5 kilogrammes per square millimetre higher than that of the latter. With rivets of length $= 1 \cdot 5d$ hand riveting shows no regularity, whereas the foregoing does apply to these short rivets riveted by the press or by the pneumatic hammer. The regularity observed in rivets of length $= 3d$ is absolutely wanting in rivets of length $= 5d$, except that in general the hardness of the pneumatic hammer and pressed rivets of this length is less, which accords with their lower tensile strength. In the case of the pneumatic hammered rivet 14B, the impressions under the heads revealed greater hardness near the edge than at the core, and these spots, as well as the hardness ordinates belonging thereto, are marked in the diagram with crosses. On the curve special branches have been drawn for them with dotted lines. In the pressed rivet 15B the hump in the hardness curve in the middle of the shank finds confirmation in the result of the tensile test on rivet 15A. The curve for the contraction of this latter rivet, shown above the hardness curve in question, plainly shows a point with diminished contraction. In both rivets the hard spot corresponds with that previously described contracted part found in measuring the released rivets. In photograph Fig. 40 this contraction can be seen on rivet 15B near the point where it has been cut. The greater hardness of the material is obviously due to the yield point having been exceeded in the cooling of the rivet.

Figs. 38 to 40 show the etched surfaces of rivet Nos. 13B, 14B, and 15B. The snap heads show the typical formation resulting from the various riveting methods. The riveting

by hand only beads the ends over and spreads out the fibres to a small extent. The pressed rivets show the strong barrel-like lateral bulge of the head, due to the high speed of working and great pressure. The pneumatic riveting, with

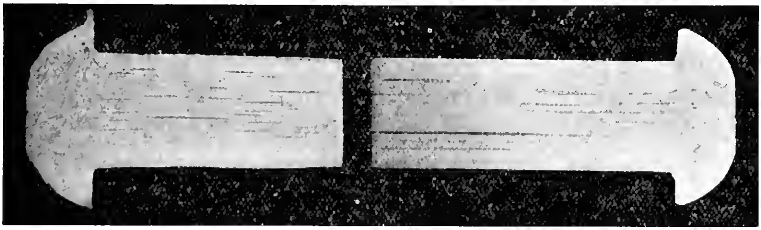
Forms of Rivet Heads.

Snaphead. Holding up Head.



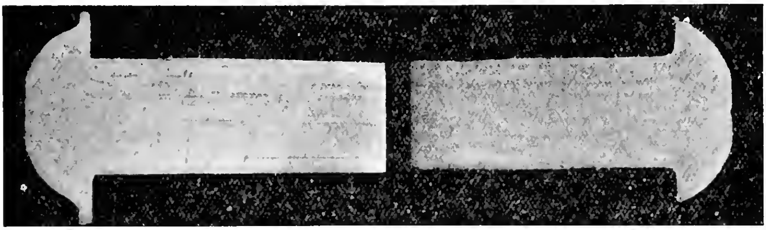
Hand Hammer.

FIG. 38.—Rivet 13B.



Pneumatic Hammer.

FIG. 39.—Rivet 14B.



Lever-Press.

FIG. 40.—Rivet 15B.

regard to the effect of speed of working, comes between the other two. The riveting method does not exercise an influence on the structure of the holding-up head, this being shaped beforehand. The segregation in the material being remarkably small, the etched surface of rivets 4B to 12B, so far as the

present examination was carried, did not reveal the influence of the riveting time on the structure of the head. Photographs were therefore not prepared.

III. SUMMARY.

The magnitude of the stresses in rivets fastened by the three methods examined is dependent on the length of the rivet shank, and in a less degree on the time expended on riveting operation. The yield point of the material fixes the limit of maximum stress.

In short rivets the stresses are in all cases less than in longer ones. In the rivets of length $=5d$ riveted by hand and by the pneumatic hammer the yield point was in some cases reached, and contraction of cross section had occurred, proving that with rivets of such proportions there is danger of their pulling in two.

With regard to the effect of time, hand riveting is the most sensitive. The effect is less marked in pneumatic riveting; and in pressed riveting the stresses, which in any case are higher than in the other two classes of rivets, are very little affected by a prolongation of the time.

The hand riveting showed the lowest stress of all, and it was only with rivets of a length $=5d$ that the values became equal to those riveted by the other two methods. With rivets of length $=3d$ and normal riveting time, the stress in the hand riveting averaged only about 60 per cent. of those in the riveting by the other two methods, both of which gave values of about 29 kilogrammes per square millimetre. With rivets of length $=1{\cdot}5d$ the stress for hand and for pneumatic riveting averaged 17·7 kilogrammes per square millimetre, and for the pressed rivets it was 25·5 kilogrammes per square millimetre. These results confirm the inferiority of hand riveting as compared with the other two methods, a fact which has been repeatedly noted with tests on resistance to slip.

The strength of the material is increased by all three methods, and with normal riveting time the increase in the strength of rivets of length $=3d$ is double the increase of

strength in rivets of length $= 5d$. By prolonging the riveting time a further increase in the strength of rivets of length $= 3d$ could be effected only by the pneumatic hammer and by the press, but the extension of the time beyond the second time scale resulted in diminishing the stress again. Of all the properties, the yield point[1] underwent the highest increase, particularly in the hand rivets of length $= 3d$. It averaged here 39·2 per cent., while in the pneumatic and press riveting it averaged 38·3 and 33·9 respectively. The breaking strength and shearing strength were both somewhat raised, the pressed rivets showing the highest increase, where it amounted for both to 21·5 per cent. In the hand riveting the increase was lowest, being 19·4 and 14·9 for the breaking strength and shearing strength respectively. In the pneumatic riveting the increase lay midway between.

For rivets of length $= 5d$ the increase in strength is only half as great, but is the same for all three methods, with the exception of the resistance to shear in the pressed rivets, which rose by only 6 per cent., as against an average of 10 per cent. in the hand and pneumatic riveting. With rivets of length $= 1·5d$, the resistance to shear was increased in the hand rivets by 8·6 per cent., in the pneumatic hammered rivets by 10·9 per cent., and in the pressed rivets by 13·5 per cent.

[1] The increase in the limit of proportionality is not considered here, as it is not taken into account in judging the quality of the rivet material. It was higher throughout than the measured stresses.

THE GASES OCCLUDED IN LIQUID STEEL.[1]

INTERIM REPORT ON THE INVESTIGATIONS CARRIED OUT AT THE STEELWORKS OF THE OUGREE-MARIHAYE COMPANY.

By Dr. L. BARADUC-MULLER (Paris).

I. General Equipment of the Laboratory.

The laboratory of physical metallurgy was built and equipped, from plans made by the author, on the level of the charging platform of the basic converters, so as to be as near as possible to the steel, when poured from the converters. It is protected from the projection of particles of incandescent slag, on tipping the converter, by a double insulating partition, and the temperature within its interior is maintained at a comfortable degree by means of a powerful Farcot fan of the air-displacement type.

The greatest difficulties were encountered in preventing the transmission of vibrations from the steelworks consequent on the blowing of the converters or the working of the overhead cranes, to the bench containing the recording instruments. Over three months were spent in solving this problem alone. Thus, in the beginning, owing to the vibrations of the steelworks, the oscillations of the "spot" in the electro-galvanometers were, before the bench was damped down, from 55 to 75 millimetres, and therefore rendered any measurement on the diagrams impossible. The oscillations are now no greater than 2 millimetres at a maximum and under the most unfavourable conditions. The details of the arrangements ultimately employed for deadening the vibrations will be given in the final report.

[1] Received May 7, 1914.

II. Recording Instruments.

The recording instruments for the physical phenomena investigated were four Chauvin-Arnoux galvanometers of the Reugade type. They served to measure:—

(*a*) The temperature of the steel during cooling.

(*b*) The absolute pressure exerted by the vacuum on the upper surface of the steel.

(*c*) The volume of gases extracted from the steel.

(*d*) The temperature of the gases beneath the cover of the experimental ingot "ladle" which contained the steel under examination.

Each photographic diagram of the recording instruments has been plotted in terms of the time. The common factor "time" is determined by a metronometer with electrical contacts, which beats periods, alterable at will, in minutes and seconds. The period of recording for each diagram can range from 4 minutes to 4 hours per revolution of the recording cylinder.

III. Appliances for creating a Vacuum above the Steel.

The apparatus for exhausting the gases consists of a Géryk-Duplex B-Fleuss pump with an exhaust capacity, at atmospheric temperature and pressure of about 30 litres per 60 revolutions per minute. This pump, which has two cylinders the pistons of which work in oil, can work in parallel or in series with the three cylinders about to be described, and can create a vacuum which can readily attain to one-tenth of a millimetre of mercury.

The three cylinders in question constitute reservoirs of exhaust for the gases to be extracted. They are immersed in running water and have a total capacity of about 600 litres at ordinary temperature and pressure. The vacuum can be maintained within $\frac{1}{2}$ millimetre of mercury (759·5 to 760) for over 24 hours, with the pumps at rest, of course.

All the piping of the installation has been carried out with

lead and copper tubing 2 millimetres in thickness, and all the joints made by soldering.

The attainment and maintenance of an almost absolute vacuum, not only in the special mould containing the steel under treatment, but in the pipes cooled by circulation, and in the taps regulating the different parts, was a problem faced with very great and protracted difficulties before it was satisfactorily solved. Thus, as regards the experimental mould intended to contain the steel, only castings made of iron and of a certain thickness were found capable of maintaining an almost perfect vacuum, whilst, on the contrary, all castings made of steel were recognised by experience as being too porous, that is, for the dimensions and the thicknesses of steel that were employed.

IV. Measuring Appliances for the Gaseous Volumes extracted from the Steel.

This apparatus serves to measure the volumes of gas, previously reduced to ordinary temperature and pressure. It is a precision gas-meter, the working, sensitiveness, and accuracy of which are checked before and after an experiment by means of a special arrangement. The needle of this meter sets in motion, by electrical contact, the "spot" of a galvanometer at every revolution.

Before this meter is placed a heavy-oil expansion pressure-regulator, the heavy oil used having a vapour-tension of *nil* at the ordinary temperature of measurements; experiments have shown that a superpressure of gas equal to a column of oil of 30 centimetres has no appreciable effect on the behaviour of this meter.

V. Method of Operation.

As soon as the $12\frac{1}{2}$ tons of steel have been poured from the converter into the casting ladle, two ingot moulds each holding 500 kilogrammes are filled, and the steel subsequently poured into the experimental ladle. This experimental ladle, lined with brickwork and fitted with a fireclay lid, has been previously heated to 1200° C. by a powerful burner fed with

compressed air and petrol vapour. In this connection, analyses of the air drawn off from the experimental ladle, after heating and before the introduction of the steel, have shown that this arrangement for heating has no appreciable action on the composition of the atmospheric gases in the ladle, and that, therefore, it should have none on the chemical composition of the gases evolved from the steel.

The conveyance of the 12½ tons of steel from the converter to the casting pit and the pouring of the two first ingots occupies about 2 minutes 40 seconds. The pouring of the steel into the experimental ladle takes about 1 minute 10 seconds. Closing the lid of this ladle requires 1 minute 20 seconds, so that the steel is subjected to the action of the vacuum at a high temperature within about five minutes of having been poured from the converter into the 12½-ton ladle. In the future two minutes of this time might perhaps be saved, and this would be the maximum speed attainable.

Throughout the whole period of heating the experimental ladle and of the steel being under treatment *in vacuo*, the india-rubber joints of the ladle and its thick iron walls are cooled by the circulation of water, which prevents, on the one hand, the india-rubber becoming heated right through, and, on the other hand, the iron walls becoming red-hot, and, from this cause, permeable by atmospheric air. Tests have shown that the temperature of the india-rubber connections has never exceeded 40° during the experiments, thanks to the water-cooling arrangements.

When the lid of the experimental ladle has been put on there is, between the surface of the liquid steel and the fire-clay cover that maintains its heat, and between the latter and the cast-iron cover, a certain space filled with a mixture of air and of high temperature gas issuing from the steel at the moment of closing the cover. This volume of gas, as well as that which is derived from the pores of the refractory bricks (and which I have termed the dead space), was determined on several occasions and at various temperatures for each experiment and found equal (for example, in the case of the last cast, No. 5, 134) to 19·5 litres at ordinary temperature and pressure. Now, as the total volume of gas extracted

from the steel in the course of this very experiment was 1,159·8 litres, under the same temperature and pressure conditions, it follows that this dead space is only

$$\frac{19{\cdot}5}{1{,}159{\cdot}8} = 0{\cdot}0168 \text{ litre}$$

and therefore practically negligible.

These things being so, and the lid of the experimental ladle having been fixed in its place, the laboratory investigation commences by the opening of the exhaust tap which connects the "dead space" with the system of tubing, in which a high vacuum obtains. This investigation consists (after, of course, carefully standardising and checking, on each occasion, the whole arrangement) in measuring and recording, in functions of the time, the manometric pressure to which the steel is subjected; its temperature; the temperature of the gases in the "dead space"; the volume of the gases extracted from the steel, after they have been brought to the normal temperature and pressure of the laboratory; and finally, in ascertaining the chemical composition of the increment of gas corresponding to each manometric pressure and corresponding temperature. The steel is left to the action of as high a vacuum as possible until it has entirely cooled; and when it is found that the pumps no longer extract any gas from the solid steel and the mercurial pressure above the steel remains constant for half an hour at practically 98 per cent. of the mercurial column in a Bunten precision-barometer, air is gradually introduced into the experimental ladle and the cover subsequently removed. The ingot is then withdrawn, freed from the little slag which inevitably accompanies it, and weighed as accurately as possible. It is then forged at about 1200°, and its truncated conical dimensions of 500 × 310 millimetres in diameter and about 500 millimetres in height are reduced to those of an ingot of 200 × 200 millimetres, and proportional length. The resulting ingot is rolled to billets of 90 millimetres square section, and these billets serve for the chemical analyses, micrographic investigations, and mechanical tests.

VI. Analyses.

In the experiments carried out on basic steel, diagrams were taken from the blowing-engines in order to ascertain, in terms of the time duration, the amount and the absolute pressure of the air blown into the converter; and, as a parallel investigation, the amount of moisture in the air was ascertained by drying, through calcium chloride tubes, a volume of 500 litres of air from the atmosphere outside the laboratory, previously filtered in order to remove the dust of the works.

The volume of each sample of gas removed in functions of the manometric pressure on the steel was 2 litres, measured at normal temperature and pressure. The gas analyses of these samples were, in each instance, made in duplicate; and the accuracy between the two results varies no more than 0·1 per cent. Side by side with the recording of the figures corresponding with each experiment an investigation was made on the possible percentage of SO_2 in the gases issuing from the steel, the large volume of gases available being employed for this purpose.

In each cast of steel made the subject of experiment the following analyses have been made in order to assemble the largest possible number of ascertainable factors capable of throwing any ultimate light on any doubtful point. With this object the following complete analyses were made:—

(*a*) The pig iron taken to the 400-ton mixer.
(*b*) The scrap, when any was used.
(*c*) The lime.
(*d*) The steel after blowing, but before the addition of the ferro-manganese.
(*e*) The two steel test-pieces taken from each end of the billet made from the ingot obtained from the centre of the cast, cast in the ordinary way and *not treated* to extract the gases.
(*f*) The two steel test-pieces taken from each end of the billet made from the ingot obtained from the centre of the cast, *treated* to extract the gases.
(*g*) The slags poured from the converter.
(*h*) The slag floating on the steel in the 12·5-ton ladle.
(*i*) The slag found on the steel within the experimental ladle.

VII. Mechanical Tests.

The mechanical tests made comparatively on the steel subjected to treatment for gas extraction and the untreated steel were carried out on test-pieces 200 millimetres long and 16 millimetres in diameter, for breaking strain, elastic limit and elongation, and on notched bar test-pieces $30 \times 10 \times 8$ millimetres, with a 1×1 millimetre notch, for brittleness, which was ascertained with a Guillery drop-weight machine, with a maximum work of 60 kilogrammetres.

The hardness tests were made with the Brinell ball-test, a 10-millimetre ball and a constant pressure of 3000 kilogrammes being employed.

VIII. Micrographic Results.

The micrographs were made at magnifications of 250 and 1000 diameters.

IX. Details of the Experiments.

These preliminary considerations being disposed of, the gross results yielded by the first six basic steel casts, which were subjected to the action of a vacuum under the circumstances detailed above, are shown in the following table:—

Table I.—*Mild Basic Steel* (38 *to* 42 *Kilogrammes per Mm.*$_2$).

No. of Experiment.	No. of Cast.	Dates (1914)	Weight of Ingot in Kilogrammes.	Volume of Gases Extracted in Litres.	Pressure and Temperature.		Approximate Ratio of Volume of Gas to that of Steel (Density of Steel taken at 7·8).
					Mms.	°C.	
1	4807	March 18	460	Experiment spoiled owing to accident.			
2	4850	March 21	543	1881·0	740	16	$\frac{1181·0}{69·5}=27$
3	4976	April 2	504	1424·7	755	20	$\frac{1424·7}{64·7}=22$
4	5052	April 10	560	1895·3	757	21	$\frac{1895·3}{71·5}=26·5$
5	5099	April 17	570	1481·0	754	22	$\frac{1481·0}{73}=20·3$
6	5134	April 24	550	1159·8	766	20	$\frac{1159·8}{70}=16·5$

In order not needlessly to extend the scope of the present report, which relates solely to the present state of the investigations on the subject, only the details of the final cast will here be given, as an example of the others.

According to these experiments it appears that the volume of gases extracted from the steel is greater the higher the amount of moisture present in the air. Thus, in casts Nos. 5099 and 5134, made in very fine weather and much dryer conditions and corresponding therefore to lower hygroscopic conditions, the volume ratio is found to be equal to 20·3 and 16·5, instead of 25·1, which corresponds with the average of the results found for the other casts, which were carried out in damp and rainy weather. The reduction of the volumes of gas obtained to 0° and 760 millimetres does not appreciably affect the results obtained.

In the detailed investigation of cast No. 5134 it will, as a matter of fact, be seen that the hydrogen derived from the dissociation of the water vapour of the air by the red-hot iron of the converter in the course of blowing forms an exceedingly important proportion of the amount of gas extracted from the steel.

The composition of the gases extracted from the steel in the course of the five experiments referred to, which were all carried out on the same quality of steel, is practically similar. It will suffice, therefore, for the present moment, to give, as an example, details of the chemical composition of the gases extracted from the steel of cast No. 5134, the record of the experimental data relating to which is given below in some detail.

Cast 5134 *Mild Basic Steel* (40 *Kilogrammes per Square Millimetre*).

1. Charge:

14,000 kilogrammes of pig iron containing—

	Per Cent.
Silicon	0·444
Manganese	0·95
Carbon	3·07
Phosphorus	1·70
Sulphur	0·095

1400 kilogrammes of lime containing—

Silica	0·90
Alumina, Ferrous oxide	1·00
Lime	95·20
Magnesia	1·00
Carbon dioxide	1·90

2. Deoxidiser—

80 kilogrammes of ferro-manganese, containing—

	Per Cent.
Manganese	81·20
Iron	11·50
Silicon	0·80
Carbon	6·30

3. Duration of blow—

10 minutes 30 seconds.

4. Beginning of aspiration of gases from the steel—

5 minutes 40 seconds after pouring the ladle of 12·5 tons.

5. Total period during which the blowing-engine was running—

10 minutes 34 seconds.

6. Volume of air blown by the blowing-engine—

5150 cubic metres at 21° and 766 millimetres of mercury. The blowing-engine slowed down after 4 minutes' blowing.

7. Absolute pressure of the air in the converter—

2·5 to 2·2 kilogrammes per square centimetre.

8. Hygroscopic condition of air blown—

5·672 grammes of H_2O per cubic metre of air at 21° and 766 millimetres.

	Kilogrammes.
9. Weights of ingots cast	12,065
,, of runners	nil
,, ladle skull	nil
,, ingot treated for gas	550
Total	12,615

10. Converter slag (weight not taken)—

Composition—	Per Cent.
SiO_2	6·5
Al_2O_3	6·1
Fe_2O_3	18·68
CaO	41·4
MnO	6·6
MgO	2·8
P_2O_5	17·2

(Sulphur not determined.)

11. Slag from the 12·5-ton ladle (weight not taken)—

Composition not determined.

12. Slag on the steel treated for gas—Weight, 0·2 kilogramme.

Composition—	Per Cent.
SiO_2	54·2
Al_2O_3	9·97
FeO	8·04
CaO	nil
MnO	27·1
MgO	nil
P	0·17
S	nil

13. Composition of the steel—

		P.	Mn.	Si.	S.	C.	Oxides.
Steel after blowing, but before adding manganese		0·043	0·270	0·0094	0·078	0·05	0·310
12,065 kilogs. of steel not treated for gas	Test-piece No. 1	0·077	0·550	0·0070	0·096	0·09	0·160
	Test-piece No. 2	0·089	0·561	0·0070	0·108	0·09	0·140
550 kilogs. of steel treated for gas	Test-piece No. 1	0·084	0·561	0·0070	0·093	0·10	0·100
	Test-piece No. 2	0·077	0·572	0·0070	0·124	0·10	0·090

14. Remarks—

The cast was satisfactorily carried out. The steel remained quiet, and did not rise in the moulds.

15. Gas meter—

Sensitiveness, 50 cubic centimetres of air at 19·2° under a pressure of 4 millimetres of water, ascertained by the electrical contact method.

Accuracy checked with 20 litres of air at 19·2° under a pressure of 4 millimetres of water. Atmospheric pressure=766 millimetres, exact to 25 cubic centimetres per 1000 cubic centimetres=2·5 per cent.

16. Staunchness of the system of tubing and of the cylinders, from the vacuum pump to the exhaust tap of the vacuum ladle, when closed—

	Millimetres.	Degrees.
Original vacuum	752·5	19·8
Final vacuum	751·5	19·4
Duration of the experiment	2 hours 47 minutes.	
Fall of mercury	1 millimetre.	
Total volume	589·2 litres.	

This fall of mercury corresponds with the entry of a volume of air equal to 0·770 litres during this period. The permeability is therefore:

$$\frac{0{\cdot}770}{589{\cdot}2}=0{\cdot}00131$$

or 0·0114 per 24 hours (1·14 per cent. per 24 hours).

17. The 1159·8 litres of gas (Table II.) therefore contained:—

	Per Gross Volume.	Per Cent.	Per Ton of Steel.
	Litres.		Litres.
Carbon dioxide	42·2	3·6	76·7
Oxygen	10·6	0·9	19·3
Carbon monoxide	352·2	30·5	640·3
Hydrogen	604·3	52·2	1098·7
Methane	2·4	0·2	4·3
Nitrogen	147·7	12·7	268·5
	1159·4	100·1	2107·8

Table II.

Time.	Depression of Mercury above the Steel.	Volume of Gases extracted by the Vacuum Cylinders.	Volume of Gases extracted by the Vacuum Pumps.	Chemical Composition of the Gases Extracted.	Remarks.
H. M. S.	Millimetres.	Litres.	Litres.	Per Cent.	
17 25 0 17 25 30	750 467 396	1st Cylinder, 0·0 83·0	0·0 53·0	CO^2 . 5·2 O^2 . . 2·0 CO . 43·2 H^2 . . 38·4 CH^4 . 0·0 N^2 . . 11·2	Opening of the aspiration tap; steel liquid at 1540° C.
... ...	396 543 444	2nd Cylinder, 72·2	57·0	CO^2 . 4·0 O^2 . . 0·8 CO . 56·8 H^2 . . 25·6 CH^4 . 0·0 N^2 . . 12·8	... ...
17 45 0	444 570 425	3rd Cylinder, 83·3	68·0	CO^2 . 4·8 O^2 . . 1·6 CO . 40·8 H^2 . 28·4 CH^4 . 0·0 N^2 . . 24·6	Total volume extracted by the cylinders and the pumps working in parallel=416·5 litres; afterwards only the pumps were working on the extraction of the gases.
17 45 0 18 1 0	425 475	...	214·3	CO^2 . 2·8 O^2 . . 0·4 CO . 24·8 H^2 . 60·0 CH^4 . 0·0 N^2 . . 12·0	Surface setting of the steel. Total volume of gas extracted from the liquid steel up to this moment=628·5 litres.
...	475 600	...	195·0	CO^2 . 2·4 O^2 . . 0·8 CO . 26·2 H^2 . . 64·0 CH^4 . 0·0 N^2 . 6·6	... ...
...	600 659	...	102·0	No analyses made.	... ...
...	659 695·5	...	111·0	CO^2 . 4·4 O^2 . . 0·4 CO . 13·8 H^2 . . 68·0 CH^4 . 0·6 N^2 . . 12·8	... ...
20 7 0	695·5 717·0	...	58·0	CO^2 . 3·6 O^2 . . 0·8 CO . 15·2 H^2 . . 66·0 CH^4 . 1·2 N^2 . . 13·2	... ...
24 0 0	717 745	...	63·0	No analyses made.	Steel at 600°; pumps stopped.
0 30 0	744·5	...	...	...	End of Experiment.
Final Volumes .		238·5	921·0	Total .	1159·8 litres at 766 mm. and 20° C.

The results of these analyses are "gross" results; that is to say that so far as the percentage of oxygen and nitrogen is concerned no deduction has been made from the total for the volume of air in the cylinders. As the pressure in the latter had been previously set at only 750 to 766 millimetres, this volume of air is practically equal to 7·740 litres. Nor has any deduction been made for the permeability of the system of piping during the whole duration of the experiments. The origin of this percentage of oxygen will be made the object of special investigations during a future research.

In the case of hydrogen, it is seen that the 5150 cubic metres of air injected into the converter contained, owing to the 5·672 grammes of water per cubic metre, 29,210·8 grammes of water capable of yielding, by complete dissociation, 3245·6 grammes of hydrogen, corresponding, at about 15° and under a pressure of 760 millimetres, with a volume of 36,058·6 litres.

Now with 1098·7 litres of hydrogen given per ton of steel, measured at the ordinary temperature, the entire cast must have contained, at a given moment, 13,860·3 litres of hydrogen. It results, therefore, that the maximum amount of hydrogen fixed, at any rate momentarily, by the steel in some form or other, dissolved or in combination, must have been

$$\frac{13{,}860{\cdot}5 \times 100}{36{,}058} = 38{\cdot}5 \text{ per cent.}$$

of the total volume of the available hydrogen.

This throws an interesting insight into the extreme solubility of the gases, and in particular of the hydrogen, in liquid steel at a high temperature. It remains to ascertain if these gases are actually in solution or in combination, and also what is left of these gases in the steels at the moment of solidification in the ordinary conditions of manufacture. The relative error corresponding with a result such as that of the cast No. 5134 can be ascertained by means of the logarithmic derivative applied to the ratio of the gaseous volumes contained to the volume of the steel containing them, calculated at 760 millimetres and 0°, the mercurial pressure having been previously corrected for the influence of capillarity.

$$S = \frac{V_{t^\circ_1}\left[(H_1 - h_1)\frac{5{\cdot}550}{5{\cdot}550 \mp t^\circ_2} + (10{,}000{\cdot}008{\cdot}38t^\circ_2)\right]}{\dfrac{\dfrac{760(1 + 0{,}003{\cdot}67t^\circ_1)}{P}}{D_{t^\circ_3}(1 + 0{,}000{\cdot}036{\cdot}8t^\circ_3}}$$

By taking into consideration, in the ratio $\frac{dv}{Vt^\circ_1}$ of the logarithmic derivative, the volume of air which corresponds with the percentage of oxygen in the final volume extracted from the steel, the relative error is found to be

$$\frac{ds}{S} = 0{\cdot}0567 \text{ whence } \frac{100ds}{S} = 5{\cdot}7 \text{ per cent.}$$

The very appreciable difference (36·6 per cent. less) which is found in the amount of iron oxides dissolved in the steel before the extraction of the gases in solution and after this operation indicate the importance of mass law and of the influence of pressure on the respective concentrations of dissolved oxides, and show the paramount part played in metallurgy, as in other sciences, by equilibrium phenomena.

X. Mechanical Tests.

The mechanical tests have yielded the following comparative results:—

	Test-piece of Metal not treated for Gases, taken from ¼ of the 90 × 90 Mms. Bars. Normal Cooling and no Heat Treatment.	Test-piece of Metal treated for Gases taken from a Rolled Round 25 Millimetres in Diameter. Normal Cooling and no Heat Treatment.
Breaking strain	40·5	44·75
Elastic limit	27·0	35·5
Elongation per cent.	28·8	24·4
Hardness	112	124
Resilience	17, 31, 19, 25 } Fibrous fracture	29, 36, 34, 34 } Fibrous fracture
	Average 23	33·2

The variations shown above exist likewise between the two sorts of steel of all the other casts. They may partly arise from the fact that the ingot treated for gases had to be forged before rolling, and that it was rolled down to a smaller diameter.

In order to obviate this source of error, modifications are in progress of being made, both as regards the shape of the ingot cast in the experimental ladle and its weight.

XI. Criticisms of the Experiments.

The first consideration which emerges from the experiments is the inadequacy of the exhaust power of the pumps even when acting in parallel with the three cylinders, for, even when working at full power, the mercurial pressure above the steel falls, just the same, from 750 to 396 millimetres.

Nothing foreshadowed such an occurrence before the experiments were undertaken. The calculations made for the apparatus and the installations were based on the certainly arbitrary assumption that the volume of the gases contained in the liquid steels would be about four times that which had hitherto been met with in laboratory investigations carried out on solid steels. This assumption, which it had been hoped would have sufficed, has been recognised experimentally as insufficient.

As a matter of fact, in the preheated experimental ladle, the 500 kilogrammes of steel remain liquid for 30 to 36 minutes without surface solidification. During this period it is, for example, possible to extract, in the case of cast No. 5134, 628·5 out of 1159·8 litres of gas, or 54·2 per cent. After this, exhaustion is applied to a steel with an exterior solid crust, which breaks down from time to time under the pressure of the gas still remaining within the core of the yet liquid steel in the centre of the ingot (as is seen by the examination of this solidified ingot, which shows that there is no well-defined pipe, and that the steel has mushroomed down). In the last resort the gases still contained in a solid body at a high temperature are extracted, and this extraction still remains easy, down to about 600°.

On the other hand, with the existing appliances, the operation occupies a long time, and the experiment becomes a tiring one, as it has to include the checking and standardisation of the apparatus, the experiment itself, and the incidental measurements, or 24 to 28 hours of consecutive laboratory work. Finally, the existing shape of the ingot has already been described as failing to respond to the requirements of the mill, or to those of the tensile tests.

For all these reasons, and by agreement with the Ougree-Marihaye Company, at whose works the author carried out these investigations, it has been decided that the shape and dimensions of the ingot to be treated shall be enlarged so that it may at once be taken to the blooming-mill and subsequently to the billet-mill without previous forging, and so undergo exactly the same metallurgical treatment as the remaining ingots of the same nominal cast, which are to serve as checks. Therefore, the whole installation is to be enlarged and the exhaust power of the pumps increased to treat a 1200-kilogramme ingot under a vacuum of 760 millimetres of mercury, irrespective of the gaseous volumes evolved during the liquid stage of the steel, so that the operation of exhausting the gases may be completed before the steel commences to solidify on the surface.

The information yielded by the five experiments referred to has therefore afforded a sure foundation, as accurate as possible, for the calculation of the new appliances and the modifications now in course of being effected. The new installation, once it is ready, will allow of a fresh report being made to the Carnegie Scholarship Committee containing a complete series of results relating to the gases occluded in dead soft steel, mild steel, hard, extra hard, and special steels, which will be manufactured in the basic converter, the basic open-hearth, and a Héroult electric furnace respectively, and will further show the exact influence of the additions made on the amounts of gas. The author conceives, however, that the experiments above described and constituting a first instalment of further researches, are of sufficient accuracy and interest as to merit their communication to the Scholarship Committee.

AN EXAMINATION OF FIRE-BRICKS[1]

AND SOME OTHER TECHNICAL REFRACTORY MATERIALS.

By W. HAMILTON PATTERSON (Birkenhead).

In all industries in which high temperatures are utilised the choice of suitable refractory materials is a factor of great importance.

The ceramic industry proper is a special example of this, because it depends on the working up of the purest, and therefore, in general, the most refractory clays.

Again, the use of electric furnaces necessitates the employment of special refractory materials. Thus the electric arc, which produces the highest temperatures known, will melt or vaporise every known substance, and yet its heat can be insulated for practical purposes almost entirely by Bath stone, because the arc produces on its surface a layer of lime which, being very slowly attacked, protects the rest of the stone.

Various products of the electric furnace, such as combinations of silicon and carbon, are special refractory materials which have special uses.

It is only proposed to consider here, however, those refractory materials which are cheap and have therefore more general application. The ordinary fire-clays are the raw materials from which the majority of these are obtained with or without the addition of other substances, such as ganister or bauxite.

Fire-bricks made from these have wide application and are selected to suit various conditions. Three large industries may be instanced—the production of iron and steel, the manufacture of glass, and the cement industry, with special reference to the lining of rotary kilns for the making of Portland cement.

In each of these industries various conditions obtain, and

[1] Received May 16, 1914.

the refractory material is chosen to comply with them as far as possible. It is not merely a question of choosing a refractory which will not melt at the temperature produced; it is one of getting a material which will withstand the influence of heat, combined with the action of the substances which it will have to contain, and of the gases, ashes, or slags which it will have to resist. In many cases ability to withstand sudden changes of temperature without cracking will have to be taken account of. What is suited to one case may be quite unsuited to another, and therefore no absolute, and at the same time general, standard of refractoriness can be set up. A brick is fire-resisting, according to Loeser, when it has proved to be resistant under given conditions of technical firing. This is a statement which may be practical, but scientifically it is not very helpful. It can be shown that it is possible to judge the merits of a fire-brick as a result of examination in the laboratory. Page and Rees [1] give the following data as necessary in the valuation of fire-clays:—

$$\text{Analysis}\begin{cases}1.\ \text{Chemical.}\\2.\ \text{Mineralogical.}\\3.\ \text{Mechanical.}\end{cases}$$

4. Specific gravity of fixed wares.
5. Porosity.
6. Limit of refractoriness.
7. Behaviour of clay when fired at intervals from cones 1 to 10.

It is only proposed at present to consider Nos. 1, 4, and 6 of these divisions in the case of fire-bricks, and to trace what connection there may be between them. Only bricks and materials which may be considered highly refractory, that is, with a melting point of 1600° C. and upwards, will be considered.

Chemical Analysis.

In view of the many discrepancies to be found in the literature where the results of chemical analysis of clays and fire-

[1] *Journal of the Society of Chemical Industry*, 1908, pp. 99–102.

bricks are recorded, it seems necessary to detail briefly the method adopted for the ultimate analyses of clays and fire-bricks made from clays which follow.[1] The sample is prepared by successive grindings and quarterings, and finally passing through a sieve of at least 90 mesh. It is then, in the case of a fire-brick, dried at about 150° C. to remove any accidental moisture.

The loss of ignition on 1 gramme is determined by heating over the blowpipe flame.

Half a gramme of the sample is fused in a platinum crucible with at least 2·5 grammes of fusion mixture ($K_2CO_3 + Na_2CO_3$), the heating being carried out carefully over a small Bunsen flame and finally over a full flame.

The melt is extracted with water and hydrochloric acid, and the whole evaporated to dryness on a water bath. It is moistened with concentrated hydrochloric acid and again evaporated to dryness. Finally, care is taken to evaporate a third time to complete dryness. This can be hastened by placing it in the air oven, but as it is not advisable to ignite the residue at a temperature of more than 110° C. to 120° C., the water bath alone is perhaps preferable.

Silica.—The whole is taken up with hot dilute hydrochloric acid and the silica filtered off and digested with some more dilute hydrochloric acid, and finally washed with hot water until the washings are free from chlorine.

This gives nearly the correct amount of silica as slight errors compensate, but its purity may be tested in the usual way by treatment with hydrofluoric acid plus a few drops of concentrated sulphuric acid.

Alumina, Ferric Oxide, Titanium Oxide, &c.—These may be determined together by double precipitation with ammonia, or determined together in one portion of the filtrate, another equal portion of the solution being reduced with hydrogen sulphide, the latter expelled by boiling and passing through carbon dioxide, and finally titrating the iron with N/50 permanganate solution.

[1] "The number of incorrect analyses of clays found in various publications is appalling, and throws doubt on many which may be worthy of full confidence."—Searle, *An Introduction to British Clays, Shales, and Sands*, p. 207 (1914).

Finally, in a part of the filtrate, usually half the amount taken for either of the above, the titanium is estimated by the well-known colour reaction of Weller, by adding hydrogen peroxide, freshly made from sodium peroxide.

If the iron and titanium are each separately determined from the alumina the precipitate is dissolved for the second time in dilute sulphuric acid instead of hydrochloric acid.

Calcium oxide, magnesia, and the alkalies are determined by the usual gravimetric methods, the Lawrence Smith method being adopted for the alkalies.

Titanium oxide is a widely occurring substance, and yet it is remarkable that if one looks up the analysis of silicates and clays in various text-books different statements are given as to its estimation. Thus in Lunge, *Technical Methods of Chemical Analysis*, it is distinctly stated that the titanium comes down with the silica.

On the other hand, Treadwell, another authority, in his well-known book on analysis, makes no mention of titanium coming down with the silica at all, but says that it is precipitated by ammonia in the iron and alumina group. The latter statement is the more correct. The following results were obtained in the case of two fire-bricks:

1. Total weight of silica residue obtained = 0·3643 gramme. 2·06 milligrammes were left after treating with hydrofluoric and sulphuric acids.

Of this 0·0005 gramme was found to be titanic oxide, which corresponds to 0·10 per cent. of titanium oxide in the total fire-brick. But in the same analysis there was also found after separation of the silica as above, with the iron and alumina, titanic oxide equivalent to 1·00 per cent. of the total brick.

2. In this case 0·17 per cent. titanium oxide was found with the silica and 0·76 per cent. with the iron and alumina. It seems probable that the amount of titanium oxide brought down with the silica increases according to the temperature to which the silica is subjected after evaporation of the hydrochloric acid. The hydrochloric acid used to dissolve the iron and alumina, &c., from the silica after final evaporation to dryness also ought not to be too diluted.

Limit of Refractoriness.

Electric Furnace.—The determinations of refractoriness were made in a specially constructed carbon tube furnace heated by an electric current. This furnace was of the simpler type described in a paper before the Faraday Society,[1] and is shown in diagrammatic form in Fig. 1.

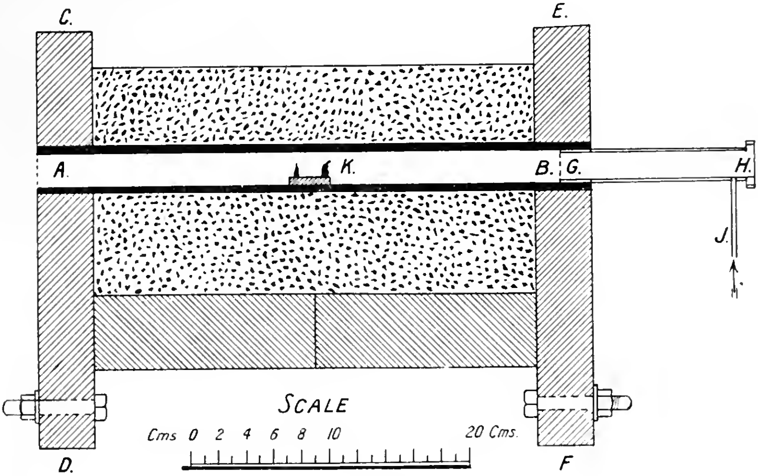


Fig. 1.

A B is an agglomerated carbon tube which is fixed firmly, either by copper strip or friction joints, into the two large graphitic pieces C D and E F.

These are made large, so as not to get unduly heated at the ends D and F where the current leads come.

The carbon tube between the graphite ends is jacketed with granular coke, which is in turn covered with fire-brick.

G H is a brass tube with a gas inlet T piece at J. At the end H is a small plate of quartz glass.

The test-pieces of the brick, which were small, pointed pieces, were placed in holes in a small graphite boat K, so that as much pointed end projected up as possible.

[1] Hutton and Patterson, "Electrically-heated Carbon Tube Furnaces"; *Transactions of the Faraday Society*, April 1905, vol. i.

The softening point was recorded when the ends began to bend slightly or round at the top, but as a rule this was not measured, being rather uncertain. The melting point was taken when they collapsed. This as a general rule was perfectly definite, and the temperature at which it occurred could be easily defined.

In the earlier experiments the pieces were embedded in magnesia, so as not to allow the fire-brick to come in contact with the graphite; later on, however, this was not considered necessary, as the surface of contact was small, and the chemical combination between the fire-brick and graphite negligible, at any rate until the former had actually melted.

In all experiments a rapid stream of hydrogen was passed through the tube, entering at J. The use of hydrogen as an atmosphere in which to conduct the experiment is less open to objection than one of any other gas.

It may be mentioned that the tube furnace described has also been used for taking the melting points of a number of ferro alloys—ferro-vanadium, ferro-titanium, &c. Some of these when heated alone melted at temperatures up to 1850° C.

The carbon tubes used were about 1 inch in diameter. Heating was generally started by a current of 50–100 amperes, which was gradually increased, the maximum current generally used being 250 amperes. The potential across the ends of the carbon tube varied between 10 to 20 volts.

An average experiment lasted 10–20 minutes, the rate of heating being made more gradual when nearing the melting point, but being rapid at first. A new carbon tube is required from time to time, but with care will last out several experiments.

Measurement of Temperature.

The temperatures were measured by a Wanner optical pyrometer sighted at the quartz glass plate H. It is important to neglect the first run of a new tube, as oily products are given off which cause a lower and inaccurate temperature reading to be given, due to absorption of light by these vapours.

The rapid stream of hydrogen between H and K keeps the tube through which the optical measurement is made clear of products of vaporisation or partial combustion. It also, in some measure, keeps the temperature uniform.

A second error to be guarded against is with an old tube making bad contact with the graphite cross-pieces, and so leading to minute arcing which will raise the temperatures at the end much more than where the boat is placed, and the pyrometer may then record this temperature. Both these sources of error can, however, be fairly easily guarded against.

As a check it was found that the same melting points were obtained for bricks using different furnaces, different pyrometers, and different observers.

Doubling the time of heating in a particular experiment led to an apparently lower melting point being obtained, but the difference brought about by doing so was not large. On the other hand, the rate at which the heating was conducted was probably in most cases too rapid for the reducing atmosphere of the furnace to have any appreciable effect on the substance used in the experiment until it had melted. When once melted a vigorous action or ebullition nearly always took place.

The measurement of temperatures higher than can be recorded by thermocouples presents many difficulties. The practical method, the use of Seger cones, is generally resorted to. For a more accurate measurement recourse must be had to an optical method. The Wanner is probably the best optical instrument for such purposes when viewing a black body, the carbon tube fulfilling the conditions for radiation from a black body.

The pyrometer is very sensitive up to 1600° C., but after that a single division on the scale corresponds to a greatly increasing temperature difference.

Unfortunately the pyrometer begins to decrease in sensitiveness at a temperature at which most fire-bricks begin to melt. The personal element in quickness of matching colour also enters into the question. From experience in measuring high temperatures the author considers the Wanner the most accurate scientific instrument at the present time.

It is not, however, so easy to use as, for instance, the Féry pyrometer.

The following is a list of some of the melting points obtained, that is to say the temperatures at which the test-pieces collapsed and flowed to a button. The temperatures are rounded off to the nearest 5° C.:

No.	Description.	Melting Point. Degrees C.
1	Fire-bricks, ordinary	1620
2	,, ,,	1610
3	,, ,,	1630
4	,, ,,	1610
5	,, ,,	1610
6	,, ,,	1660
7	,, ,,	1680
8	,, ,,	1865
9	,, ,,	1735
10	,, ,,	1860
11	,, ,,	1735
12	,, ,,	1735
13	Dinas silica brick	1680
14	Magnesite brick	1860
15	Special block	More than 1915
16	Bauxite brick	1770
17	Chrome iron ores	1730
18	,, ,,	1725
19	,, ,,	1630
20	,, ,,	1545
21	,, ,,	1630
22	Bone ash cupel	1865

Analysis of some of these samples are also appended. It is hoped shortly to extend this list considerably by filling in the gaps; rational analyses are also in progress.[1] It will then be possible to go more fully into the relations between chemical constitution and refractoriness, and to throw some light on contradictory statements which have been made, *e.g.* Bischoff (1860), Seger, Richters (1868), Bourry, Dunn,[2] Weber,[3] Ludwig (1905), Heraeus,[4] Lange,[5] &c.

[1] "At present so little is known as to physical requirements for refractory articles in certain industries that there is a wide scope for investigation in this direction."—Searle, *An Introduction to British Clays, Shales, and Sands*, p. 360 (1914).

[2] Dunn, "Fusion of Refractory Materials"; *Journal of the Society of Chemical Industry*, 1904, pp. 1132–4.

[3] Weber, *American Institute of Mining Engineers*, September 1904.

[4] Heraeus, *Z. angew Chem.*, 1905, vol. xviii. pp. 49–53.

[5] Lange, *Stahl und Eisen*, 1912, pp. 1729–37. *Cf.* also "Standard Specifications for Refractory Materials"; *Report of Committee of the Institution of Gas Engineers*, 1912.

Ultimate Analysis.

No.	Specific Gravity.	Silica per Cent.	Alumina per Cent.	Ferric Oxide per Cent.	Titanium Oxide per Cent.	Total $Al_2O_3+Fe_2O_3+TiO_2$ per Cent.	Calcium Oxide per Cent.	Magnesia per Cent.	Alkalies per Cent.	Loss on Ignition per Cent.
9	2·176	57·0	...	...	...	39·6	0·60	0·45	...	...
10	2·139	66·0	...	...	...	31·5	0·44	0·52	...	0·05
11	2·220	73·2	18·3	6·6	0·40	25·3	0·04	trace	0·5	0·22
12	2·185	74·4	...	...	...	23·3	0·88	0·45	...	0·31
13	2·162	96·6	...	...	...	0·35	1·50	0·06	...	...
16	2·380	57·1	36·0	4·6	1·44	42·0	0·34	0·06	...	...

The only paper giving an extended series of observations on melting points with the help of modern pyrometry, but without analytical data, is one by Kanolt in America,[1] who used an Arsem graphite resistance furnace and a Morse optical pyrometer of the Holborn Kurlbaum type.

The question of choosing suitable refractory material for the lining of the clinkering zone of rotary kilns for the production of Portland cement is of interest and also of importance. As the brick will have to contend against highly basic substances it may be naturally supposed that a basic brick will best fulfil the conditions required.

An examination of a brick which gave very satisfactory results in practice, however, led to the following results:—

Melting point	1735° C.
Density	2·217
Ultimate analysis—	
Silica	73·2 per cent.
Alumina	18·3 ,,
Ferric oxide	6·5 ,,
Titanium oxide	0·4 ,,
Calcium oxide	0·4 ,,
Magnesia	trace
Alkalies	0·50 ,,
Loss on ignition	0·22 ,,

The explanation of the success of such a brick for the purpose is given from the fact that it fuses on the surface, and

[1] *Journal of the Franklin Institute*, 1912, vol. clxxiv. pp. 225–27.

forms with the cement clinker a protective coating which prevents further attack.

The question of protective coatings is thus important in judging the practical refractoriness of fire-bricks, and it will be considered later.

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